# THE STUDY OF METHOD FOR SUPRESSING TRIPLEN HARMONIC PRODUCED BY SYNCHRONOUS GENERATOR

BY

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A dissertation submitted to the
Electrical & Electronic Engineering Programme
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Bandar Seri Iskandar, 31750 Tronoh, Perak

# CERTIFICATION OF APPROVAL

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Approved:

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TRONOH, PERAK
SEPTEMBER 2011

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Muhammad Arif Bin MdNor

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# ABSTRACT

Harmonic can and often be found in generator. It is proved by the published journal that generator can produced harmonic. There are many types of generator such as synchronous generator and induction generator but this paper will only focus on synchronous generator. Third harmonic is being focus in this paper which gives the most influence in triplen harmonic magnitude that is produce by synchronous generator. The objective of this paper is to find alternatives to suppress triplen harmonic produce by synchronous generator. Besides, fundamental about triplen harmonic will be studied. The author also will try to model circuit by simulation. The cause and effect of harmonic to the generator also will be reviewed. There is already many ways to reduce triplen harmonic but it is not specify for generator. So, this paper will apply all possible method to be implemented to the generator with hope that harmonic could be reduced. Method such as load variation, generator neutral earth resistance (NER), tuned Peterson coil and untuned Peterson coil method could suppress the triplen harmonic produced by synchronous generator. However, research show that delta configurations could not reduce triplen harmonic. Hope fully this research will help people in industrial business realize the cause and effect of harmonic and help them to reduce triplen harmonic produce by their generator.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Two generating units at gas district cooling (GDC) plant located in Universiti Teknologi PETRONAS (UTP) are being used to supply electricity for whole campus. UTP power system is operated with 2 modes which are island mode and parallel mode. Under normal operation, UTP power system is operating in island mode and during emergency, it will be connected to utility grid of Tenaga Nasional Berhad (TNB). Each generating unit grounding is being installed with neutral earthing resistor (NER). It has been identified that when generator operating in parallel with the grid, the NER temperature increased. Details study of the case reveals that triplen harmonics currents continuously flow through NER during both modes. Parallel operation cause higher triplen harmonics currents compared to island mode of operation. Increase in triplen harmonics currents that flow through NER lead to high temperature of it. Investigations on UTP electrical distribution show that generators are producing triplen harmonic. Based on this result, further study will be conducted to find alternatives to suppress triplen harmonic currents produce by these generators.

## 1.2 Problem Statement

Finding show that generator NER temperature increases when the generator operating parallel with the grid. Excessive heat which are come from generator NER cause NER cable to damage. Future concern with this continuous excessive heating is the reduction of insulation life that can lead to failure. So far, prevention step taken by UTP to reduce NER temperature is by having louvers at all four side of generator NER. This step manages to slightly reduce heat from NER generator. However this is not electrical engineering solution but mechanical solution. So, this research is to find solution using electrical engineering solution.

## 1.3 Objective

1. To learn about fundamental of triplen harmonic
2. To study about triplen harmonic cause & effect produced by synchronous generator
3. To model circuit for simulation
4. To study possible methods for suppressing third harmonic produce by synchronous generator.

## 1.4 Scope of Study

1. Research on triplen harmonic through past journal, thesis and books.
2. Simulation of possible methods for lab experiment

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Fundamental of Triplen Harmonic

Third harmonic is a major component of triplen harmonics [1]. Triplen harmonics current and voltage are the odd multiples of third harmonics ($3^{rd}$, $9^{th}$, $15^{th}$ etc). Symmetrical triplen harmonic are zero sequence in nature because their phase quantity having same magnitude and phase angle [2]. The source of triplen harmonics in synchronous generators depending on its winding design in term of pitch factor, distribution factor and slot skew [2,3]. The third harmonic phase voltage causes the form of circulating currents at third harmonic frequency. The magnitude of this current is determined by the third harmonic driving voltage and the third harmonic impedance of the zero sequence networks [4]. Balanced third harmonic exist in each of three phases. While the fundamental frequency voltages in the three phases are displaced 120 electrical degrees in time-phase, the third harmonic voltages are displaced 3 x120 = 360 electrical degrees (see figure 1). Thus it shows that three third harmonic voltages are in the same phase [4].

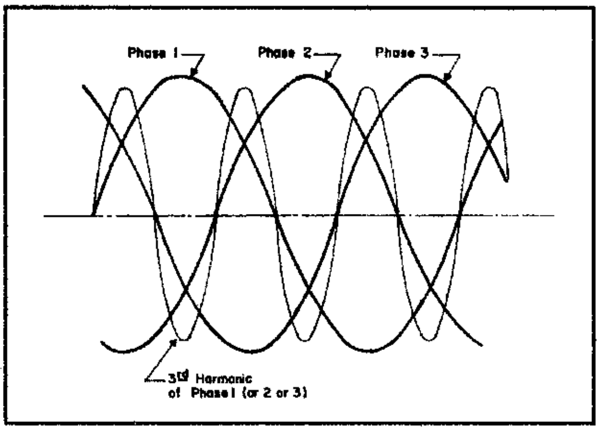



**Figure 1: Fundamental & third harmonic frequency voltage waveform on three phase system.**

There are no even harmonic because they cancel each other for half symmetry waveform. Assuming a balanced, three phase, grounded –neutral, wye-connected load, the positive and negative sequence currents, all of equal magnitude and rotating 120 degree apart, add vectorially and cancel at any common point of connection as given below[5]:

$$I_{a+}\,\underline{/0} + I_{b+}\,\underline{/120} + I_{c+}\,\underline{/240} = 0\text{ A}$$
$$I_{a-}\,\underline{/0} + I_{b-}\,\underline{/240} + I_{c-}\,\underline{/120} = 0\text{ A}.$$

It is contrary for zero sequence current which is same in magnitude and in phase with each other are additive on common neutral conductors as given below [5]:

$$I_{a0}\,\underline{/0} + I_{b0}\,\underline{/0} + I_{c0}\,\underline{/0} = 3(I_{a0}\,\underline{/0})\text{ A}.$$

Non linear device/load (e.g. iron core reactor) and switched electronics device (e.g. iron-core reactor) are also produce triplen harmonics [6].

## 2.2 Cause & Effect of Triplen Harmonic

There are many cause and effect cause by triplen harmonic. Triplen harmonic can cause current-responsive ground fault protection relays to operate in the absence of actual fault conditions. This might be happen when the magnitude of harmonic current in the neutral is large enough. To protect from false tripping, relay need to be desensitized which will cause the efficiency of the relay become lesser [4].

The existences of harmonic current are causing the possibility of experiencing parallel resonance problem in a distribution system containing power capacitors increasing. Parallel resonance leads to harmonic related heating including blown fuses, circuit breaker overheating and unexplained general equipment failure. Resonance is the condition when magnitude of the inductive reactance of the system is equal to the capacitive reactance of the capacitor bank, essentially canceling both [6].

Some of it is triplen harmonics cause the neutral earthing resistor (NER) temperature become high. Triplen harmonic currents add up at the neutral under balanced load. So, the magnitude of triplen harmonic current at the neutral is three times the phase triplen harmonic currents. The continuous of flow of triplen harmonics currents through NER cause the increasing NER temperature [7].

Noise interference also cause by triplen harmonic. A harmonic analysis of the generator earth current showed that triplen harmonics, more focus on $9^{th}$ harmonic was in series resonance with the telephone line system capacitance. Further measurements identified that these triplen harmonic were inducing significant voltages in the telephone system. $9^{th}$ harmonic is 50 times as effective as the third harmonic in creating noise interference [9].

The presence of triplen harmonics voltages lead to multiple zero crossing in phase to neutral voltage waveform causing the voltage zero crossing based detection lighting control system to malfunction [13]. Triacs are being use to control theatrical lighting. Triacs varies the rms value of voltage supplied by controlling the phase angle of the supply voltage. A large harmonic distortion will be produced to the load current when controlling the phase angle of the supply voltage.

Besides, triplen harmonics have been recognized to raise the neutral to earth voltage. Neutral to earth voltage is the voltage measured between the system neural and remote earth. Neutral current flow between the neutral and the earth determine the voltage. Triplen harmonic, mostly the third add in the neutral. Larger neutral current will increase neutral to earth voltage [16].

Triplen harmonics that add in neutral cause the increase of magnetic field in the vicinity of the lines. Magnetic field will exist at specific frequency if harmonic currents are present. Currents in each phase become larger due to harmonic currents. From Biot-Savart Law or Ampere's circuital law, it proves that magnetic field is proportional to the current [16].

## 2.3 Method of suppressing triplen harmonic

One of the methods of suppressing triplen harmonic is restricting the production of triplen harmonics currents. This approach requires identification of triplen harmonic currents sources whether from generator or non-linear load. At the moment of harmonics sources have been detected, further action need to be taken to reduce harmonic such as install a filter.

Size of cable also influences the magnitude of triplen harmonic that go through the cable. The third harmonic current magnitude increased with larger cable size. It is because larger cable size has lower impedance [1].

Furthermore, winding configuration in figure 2 also take part in suppressing triplen harmonic. In this context, delta configuration will be used. If the primary side use delta configuration, the third harmonic will be circulating in primary winding. This leads to no or reduce of triplen harmonics currents in secondary side/ winding [2].

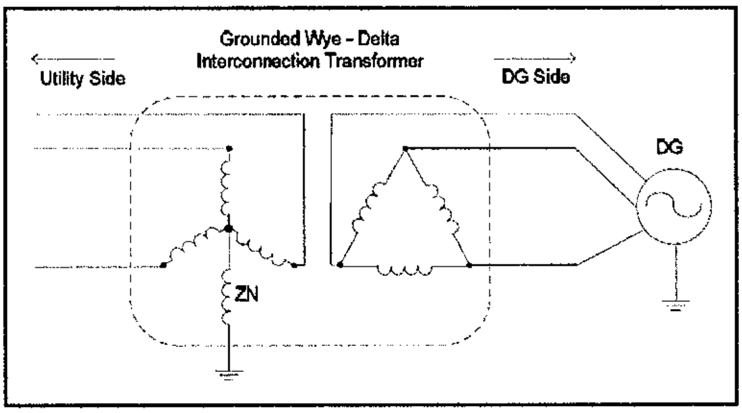



**Figure 2 : Example of transformer with delta configuration**

Less triplen harmonic currents can be produced if using generator with 2/3 armature winding pitch [4, 7]. Many domestic generator builder use a pitch close to 5/6. It is because the designs of 2/3 pitches more costly, less efficient, and operate at higher field temperatures compare to machine with higher pitch factors [4].

Increasing zero sequence impedance in the network is also one of the methods. It depends on the magnitude of zero sequence impedance in the network that can be increased by utilizing correct grounding method [4]. Addition of impedance in the neutral grounding connection also can reduce the circulating currents [3]. The circulating current is cause by triplen harmonic. Voltage difference is proportional to the production of circulating neutral currents. Small voltage conflicts seem avoidable but small voltage across the low impedance of a solid ground can produce substantial currents. This current should be reduced. Grounding methods that can be applied are:

1. Low resistance grounding
2. Reactance grounding
3. Solid grounding
4. Group resistance grounding.

Oversized transformer can suppress triplen harmonic. In distribution circuit, the transformer represents a majority of the source impedance. The inductive component of the transformer can act as a significant opposition reactance to the flow of harmonic current, tending to damp them [5]. It is happen due to skin effect at harmonic frequencies. The higher the frequency of the harmonic, the more the transformer will act to suppress that harmonic component in the load current [5, 14].

Furthermore, double the neutral wires can be used to avoid harmonic problem [8]. Modify a system from 4-wires system to 6 wire system. Each phase has their individual neutral wires. The harmonic suppression system (HSS) is totally different method. It reduces triplen harmonic currents produce by non-linear load. It is a passive device, consisting of a parallel resonant tank circuit tuned to third harmonic and inserted at the transformer [8]. It is connect in series with neutral wires to the load. The installation of the HSS can be seen in figure 3.

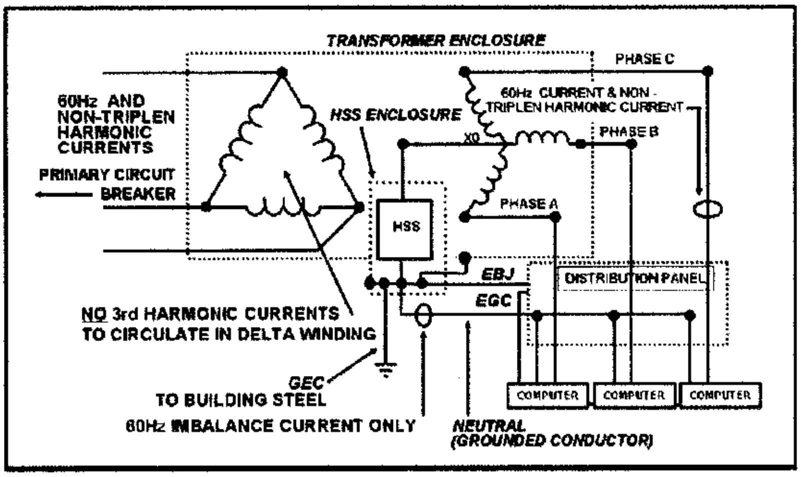



**Figure 3 : The installation of HSS can reduce harmonic**

Filtering is also an alternative to reduce triplen harmonic [9]. LC filter is one of the choices. It requires high Q filter for LC filter to operate efficiently. The effectiveness of this method was uncertain because third harmonic was still detected. Another filter option is active filter. The proposed connection is an active filter inverter connected with neutral conductor in series to suppress the zero sequence current harmonics of the neutral conductor [10]. Figure 4 show the suggestion connection.

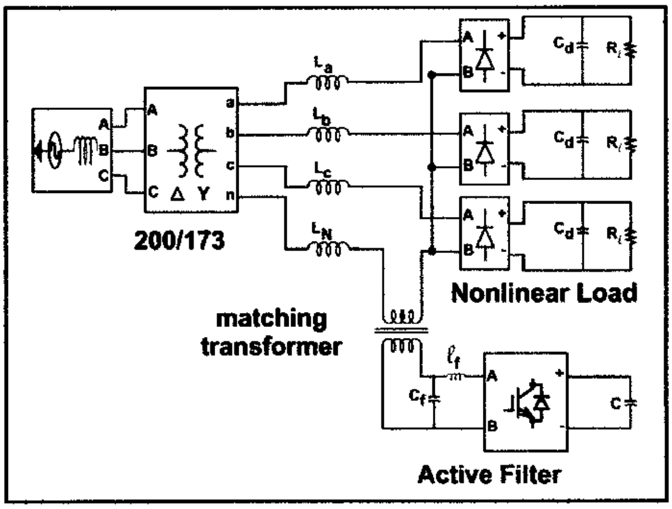



**Figure 4 : The suggestion connection of active filter**

There is also another configuration of active power filter called novel series active power filter [11]. It is effective for voltage harmonic compensation of voltage-source type harmonic source. Figure 5 show the configuration of this filter.

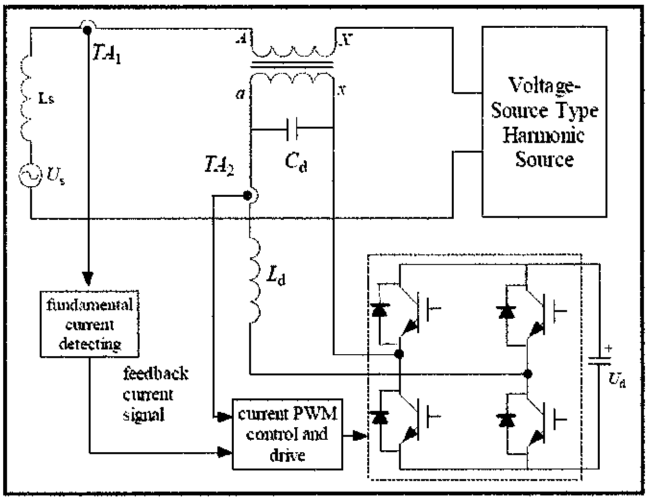



**Figure 5 : Configuration of the novel series active power filter**

Other filters that can reduce harmonic such as [12]:

1. Standed single frequency
2. Notch filter
3. Multifrequency filter
4. High pass filter
5. H type filter
6. Zero Sequence Harmonic Filter
7. Combined Zero Sequence Harmonic Filter
8. Matrix harmonic filter
9. Hybrid harmonic filter

Besides, the arrangement of neutral conductor also play role on determine the magnitude and harmonic distortion of the neutral to ground voltage [13]. The arrangement of cable in figure 7 is better compared to arrangement of cable of figure 6 in order to reduce harmonic distortion.

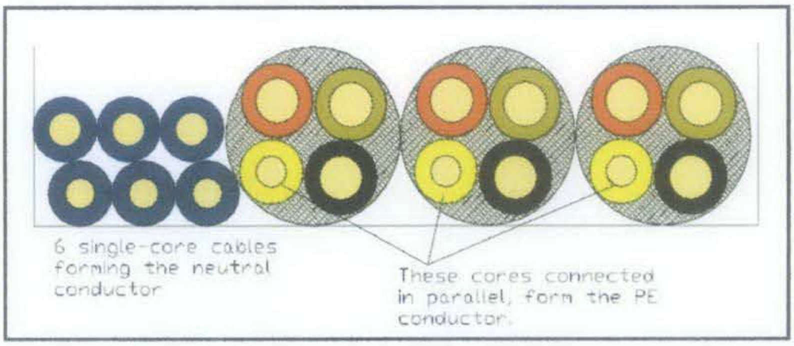



**Figure 6 : Neutral conductor doubled in cross section**

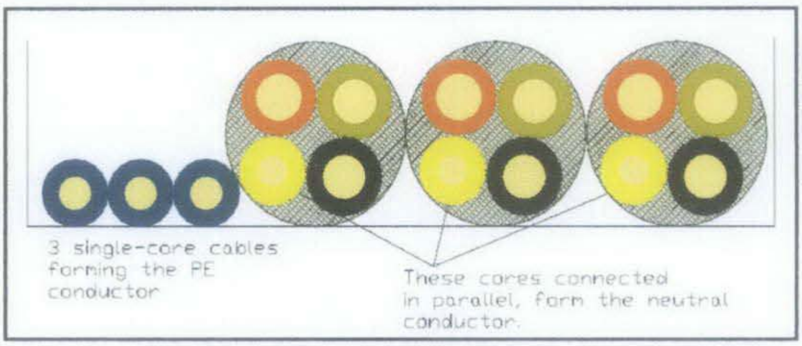



**Figure 7 : The neutral is formed by the fourth core of the multicore cables**

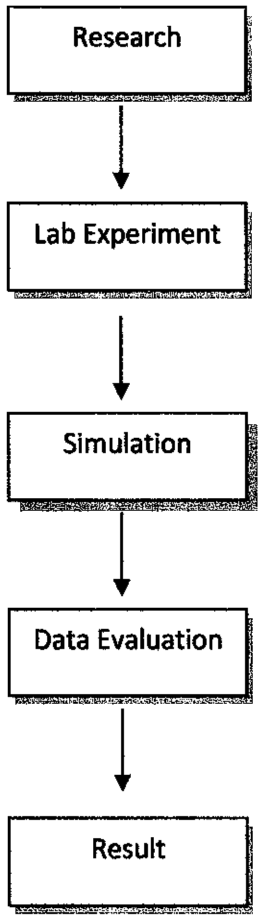
Shunting triplen harmonics currents to earth is also a method. For this purpose, phase shifting transformer or zigzag earthing transformer can be use to prevent the triplen harmonic currents propagate into the network [4, 7, 8, 9, 15]. For the operation, the harmonic currents flow to the transformer secondary winding from harmonics generating load. By vector analysis, with all triplen-harmonics current are in phase with each other, triplen harmonic will be reduced by the positive and negative flux interaction in the zigzag [15].

Other alternatives that might be considered to be used are installation of Tuned Peterson Coil. It is a grounding method which connected to neutral point earthed. The earth connection will be directly connected to resistor parallel with inductor. Along the load, there will be capacitance attach to the line. The value of impedance for capacitor and inductance must be same for Tuned Peterson Coil to work correctly [17].

# CHAPTER 3

# METHODOLOGY

## 3.1 Methodology




Firstly a research about triplen harmonic will be conducted such as how triplen harmonic happen, the effect of triplen harmonic to the machinery, the possible methods to suppress triplen harmonic and so on. Published journal or theses are being collected and information inside it will be use for future reference.

Next, when the possible method of suppressing triplen harmonic have been identify, the author try to implement the methods found in lab experiment. On lab experiment, the connection is being set up with the supervision of competent staff. Special equipment which is FLUKE power analyzer that can analyze triplen harmonic is being attached or clamp to the circuit connection to identify the existence of the harmonic.

Using data from lab experiment, the author simulate the real lab connection using software call PSCAD. Both data from simulation scheme and lab experiment configuration are collected. The data will be analyzed. The results which are getting from here will prove either the methods is effective or not based on the objective of the case study conducted.

Table 1 show the laboratory equipment ratings for equipment use in experiment such as generator, transformer and load.

**Table 1 - Laboratory equipments ratings**

| Equipment | Ratings |
|---|---|
| Generator | 415 V;2.1 A;2 kW |
| Transformer | 415 V/240 V;250 VA |
| Resistive Load | 415 V;1040 W |
| Inductive Load | 415 V;1040 Var |

There are 3 scenario need to be conducted for lab experiment:

1. Single Generator
2. Parallel between Grid and Generator
3. Parallel between 2 Generators

Each scenario has four parts of experiment to cover.

A. Load Variation

   Only balanced load situation are studied for resistive load, inductive load and combination of both load. It is a direct connection from generator to the load. Currents and voltage of harmonics are measured at generator side only since value of harmonic voltage at load side is highly dropped. Table 2, 3 and 4 are details of value for resistive, inductive and combination of both load impedance respectively.

**Table 2 - Value of resistive load**

| Resistive Load (Ω) |
|---|
| 120 |
| 160 |
| 240 |
| 320 |
| 480 |

**Table 3 – Value of inductive load**

| Inductive Load (H) |
|---|
| 0.38 |
| 0.51 |
| 0.76 |
| 1.02 |
| 1.53 |

**Table 4 – Value of resistive & inductive load**

| Case | Resistive & Inductive load (Ω + H) |
|---|---|
| Case 1 | 120 + 0.38 |
| Case 2 | 160 + 0.51 |
| Case 3 | 240 + 0.76 |
| Case 4 | 320 + 1.02 |
| Case 5 | 480 + 1.53 |

B. Generator NER

By using balanced resistive, inductive and combination of both loads, the value of NER is varied. The value of load is being setup up to constant. NER is being connected to neutral wire which flow through generator neutral. Currents and voltage of harmonics are measured at generator side only since value of harmonic voltage at load side is highly dropped. Table 5 below show the value of NER use for the experiment:

**Table 5 – Value of NER use for experiment**

| NER (Ω) | Resistive Load (Ω) | Inductive Load (H) | Resistive & Inductive load (Ω + H) |
|---|---|---|---|
| 138 | 160 | 0.38 | 120 + 0.38 |
| 172 | 160 | 0.38 | 120 + 0.38 |
| 229 | 160 | 0.38 | 120 + 0.38 |
| 343 | 160 | 0.38 | 120 + 0.38 |
| 686 | 160 | 0.38 | 120 + 0.38 |

C. Tuned Peterson Coil

For Tuned Peterson Coil, there are 3 items need to be installed together such as capacitor, resistor and inductor. Resistor and inductor need to be parallel connected at the neutral grounding while capacitor representing cable capacitance is being attached along the connection between generator and load. For the experiment, the value of load is constant. The value of resistance, inductance and capacitance are varied like in table 6 below. The impedance of inductor and capacitor are needed to be set with same value for Tuned Peterson Coil to work properly. Loads are connected to generator neutral points. Currents and voltage of harmonics are measured at generator side only since value of harmonic voltage at load side is highly dropped.

**Table 6 – Value of Tuned Peterson Coil use for experiment**

| Tuned Peterson Coil (Ω + H + μF) | Resistive Load (Ω) | Inductive Load (H) | Resistive & Inductive load (Ω + H) |
|---|---|---|---|
| 138 + 7.6 + 1.33 | 160 | 0.51 | 120 + 0.38 |
| 172 + 5.08 + 1.99 | 160 | 0.51 | 120 + 0.38 |
| 229 + 3.8 + 2.65 | 160 | 0.51 | 120 + 0.38 |
| 343 + 2.53 + 3.98 | 160 | 0.51 | 120 + 0.38 |
| 686 + 1.69 + 4.64 | 160 | 0.51 | 120 + 0.38 |

D. Untuned Peterson Coil

The method is same like Tuned Peterson Coil. The only different is the capacitor is being taken out from the connection.

E. Delta Configurations

There are three possible delta configurations of transformer such as delta-delta, star-delta and delta-star. The generator is connected to transformer at primary winding directly and the secondary winding is connected to balanced resistive load directly. Loads are connected with neutral wire which connected to transformer (only for star winding only) and to generator neutral points. Currents of harmonic are measured at the generator side, transformer primary and secondary side and at end of load side.

### 2.2 Gantt chart

| No. | Details / Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FYP 1 | | | | | | | | M | | | | | | | |
| 1 | Selection of Project Topic | | | | | | | | I | | | | | | | |
| 2 | Preliminary Research Work | | | | | | | | D | | | | | | | |
| 3 | Submission of Extended Proposal | | | | | | | | | | | | | | | |
| 4 | Modeling Work | | | | | | | | S | | | | | | | |
| 5 | Simulation Work | | | | | | | | E | | | | | | | |
| 6 | Lab Experiment | | | | | | | | M | | | | | | | |
| 7 | Proposal Defend | | | | | | | | E | | | | | | | |
| 8 | Submission of Draft Report | | | | | | | | S | | | | | | | |
| 9 | Submission of Interim Final Report | | | | | | | | T | | | | | | | |
| | | | | | | | | | E | | | | | | | |
| | FYP 2 | | | | | | | | R | | | | | | | |
| 1 | Lab Experiment | | | | | | | | | | | | | | | |
| 2 | Modeling work | | | | | | | | B | | | | | | | |
| 3 | Submission of progress report | | | | | | | | R | | | | | | | |
| 4 | Poster presentation | | | | | | | | E | | | | | | | |
| 5 | Submission of draft report | | | | | | | | A | | | | | | | |
| 6 | Submission of final report | | | | | | | | K | | | | | | | |

Milestone

Process

# CHAPTER 4

# LAB EXPERIMENT RESULT & DISCUSSION

To study the methods of reducing triplen harmonic produce by synchronous generator, the magnitude of voltage, current and phase angle are significance.

Therefore, the measurement for fundamental and third harmonic voltage, current and phase angle are studied and presented below to observe the effects of method applied.

## SINGLE GENERATOR

### 4.1 Variation Load

#### 4.1.1 Balanced Resistive Load

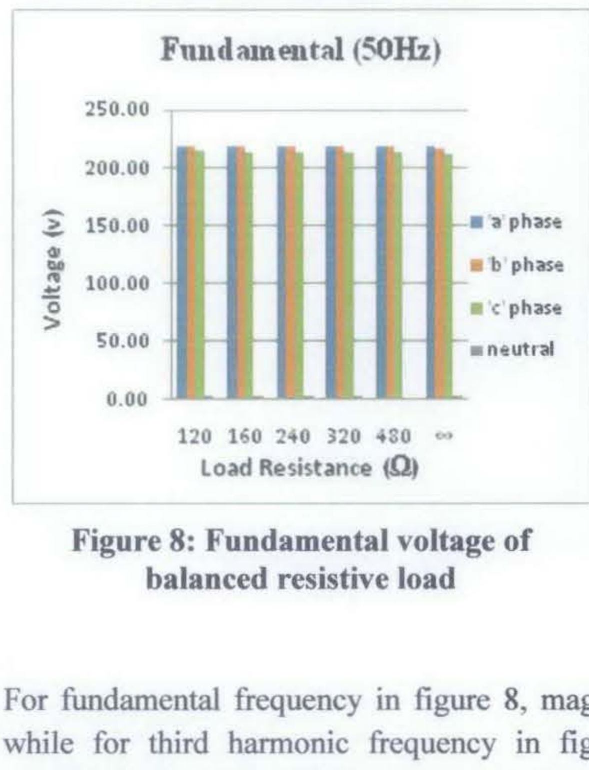



**Figure 8: Fundamental voltage of balanced resistive load**

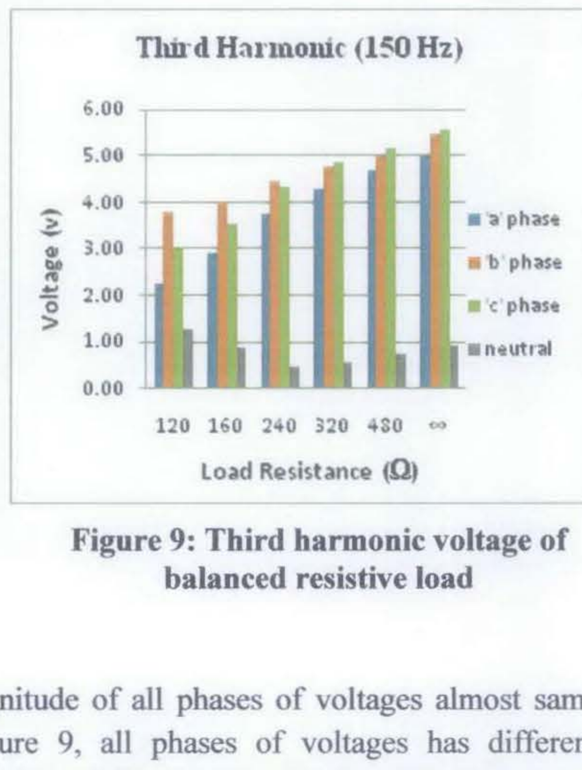



**Figure 9: Third harmonic voltage of balanced resistive load**

For fundamental frequency in figure 8, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 9, all phases of voltages has different magnitude. As load resistance increase, magnitude of third harmonic voltage also increases. The highest third harmonic voltage is measured when there is no load supplied. The third harmonic voltage has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic voltage with 120 ohm are used to plot phase angle diagram as in figure 10 and figure 11.

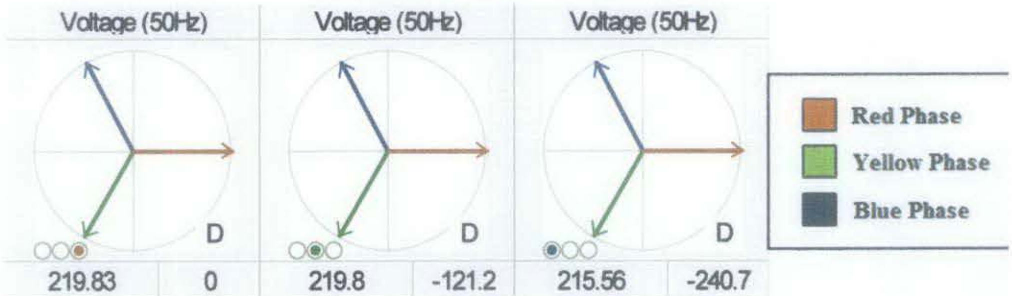



**Figure 10 : Fundamental voltage phase angle diagram of balanced resistive load**

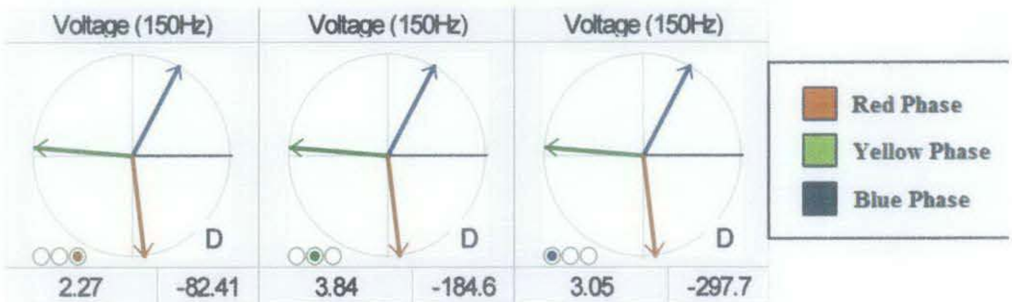



**Figure 11: Third harmonic voltage phase angle diagram of balanced resistive load**

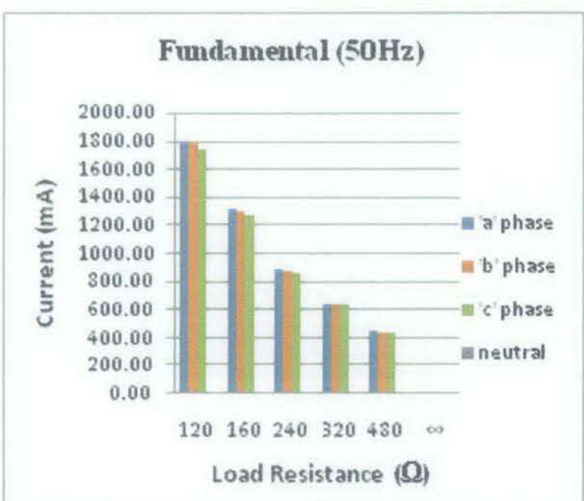



**Figure 13: Fundamental current of balanced resistive load**

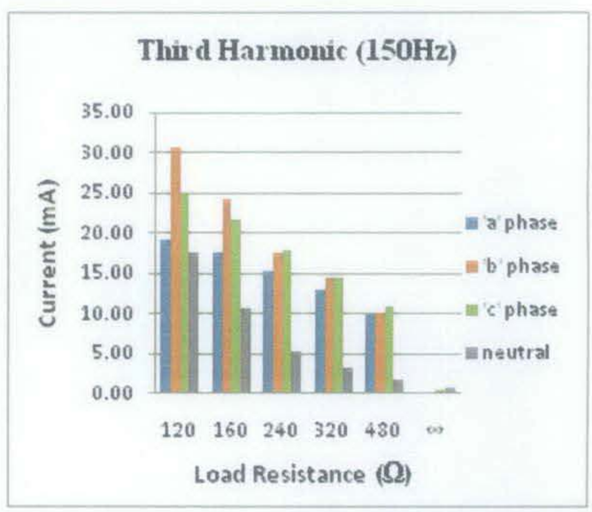



**Figure 12 : Third harmonic current of balanced resistive load**

For fundamental frequency in figure 12, magnitude of all phases of current is approximately same while for current of third harmonic in figure 13, all phases are different. There is almost no neutral current for fundamental frequency. The magnitude of phase and neutral current for third harmonic frequency is decreasing as the load impedance is increasing. The third harmonic neutral current is not three times the phase current due to positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic current with 120 ohm are used to plot phase angle diagram as in figure 14 and figure 15.

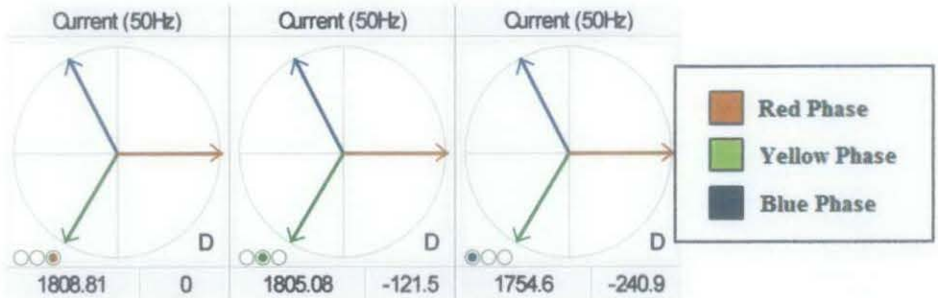



**Figure 14 : Fundamental current phase angle diagram of balanced resistive load**

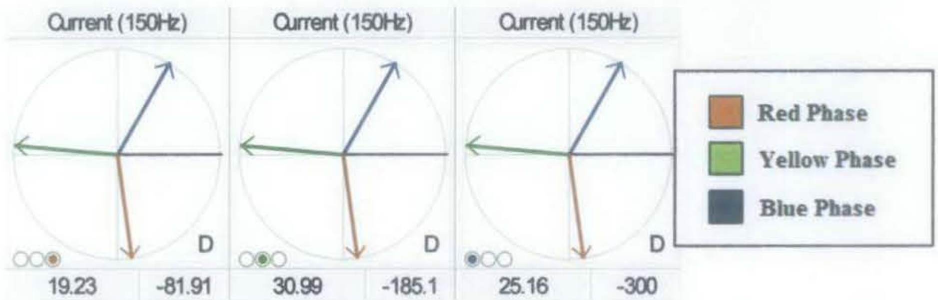



**Figure 15: Third harmonic current phase angle diagram of balanced resistive load**

Table 7 show the third harmonic neutral current reducing as the load impedance is increasing.

**Table 7 - Magnitude of third harmonic neutral current vs. resistive load**

| Load (Ω) | Neutral Current (mA) |
|---|---|
| ∞ | 0.84 |
| 120 | 17.77 |
| 160 | 10.90 |
| 240 | 5.49 |
| 320 | 3.25 |
| 480 | 1.77 |

### 4.1.2 Balanced Inductive Load

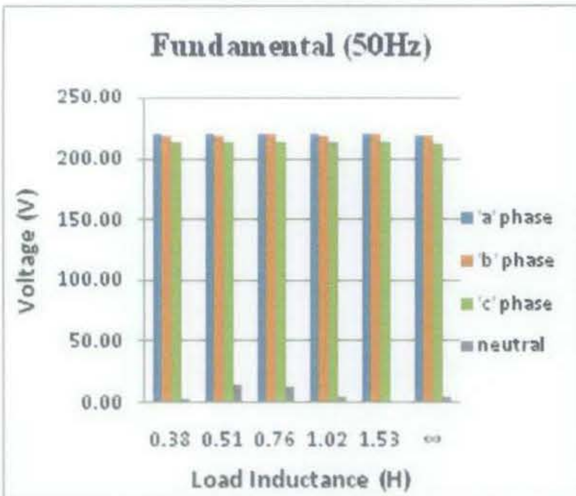



**Figure 16 : Fundamental voltage of balanced inductive load**

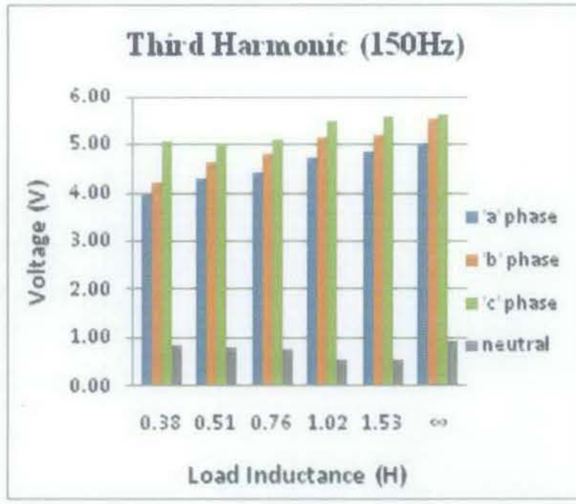



**Figure 17: Third harmonic voltage of balanced inductive load**

For fundamental frequency in figure 16, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 17, all phases of voltages has different magnitude. As load inductance increase, magnitude of third harmonic voltage also increases. The highest magnitude of third harmonic voltage is measured when there is no load supplied. The third harmonic voltage has positive sequence of phase angle.. Examples of phase angle data for fundamental and third harmonic current with 0.38 Henry are used to plot phase angle diagram as in figure 18 and figure 19.


**Figure 18: Fundamental voltage phase angle diagram of balanced inductive load**

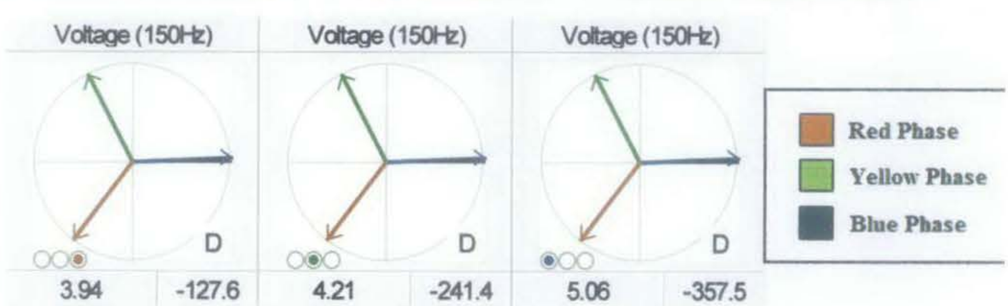



**Figure 19: Third harmonic voltage phase angle voltage of balanced inductive load**

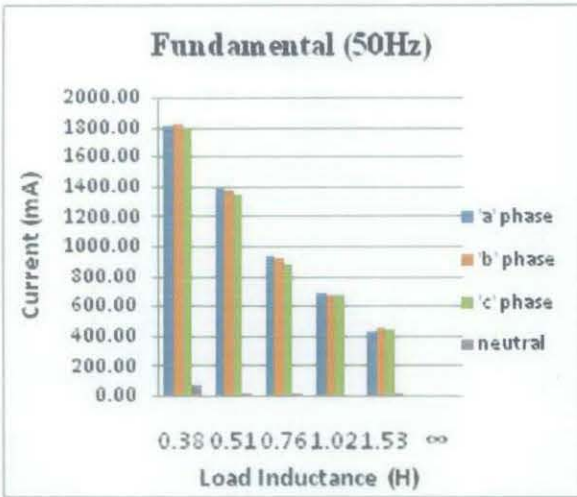



Figure 20: Fundamental current of balanced inductive load

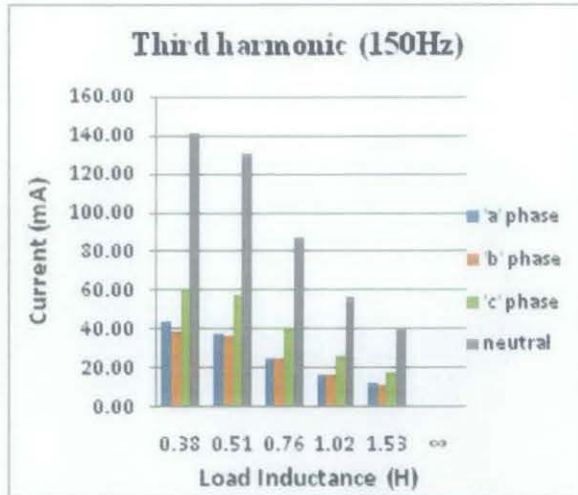



Figure 21: Third harmonic current of balanced inductive load

For fundamental frequency in figure 20, magnitude of all phases of current is approximately same while for current of third harmonic in figure 21, all phases are different. There is almost no neutral current for fundamental frequency. The magnitude of phase and neutral current for third harmonic frequency is decreasing as the load impedance is increasing. The third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Examples of phase angle data for fundamental and third harmonic current with 0.38 Henry are used to plot phase angle diagram as in figure 22 and figure 23.

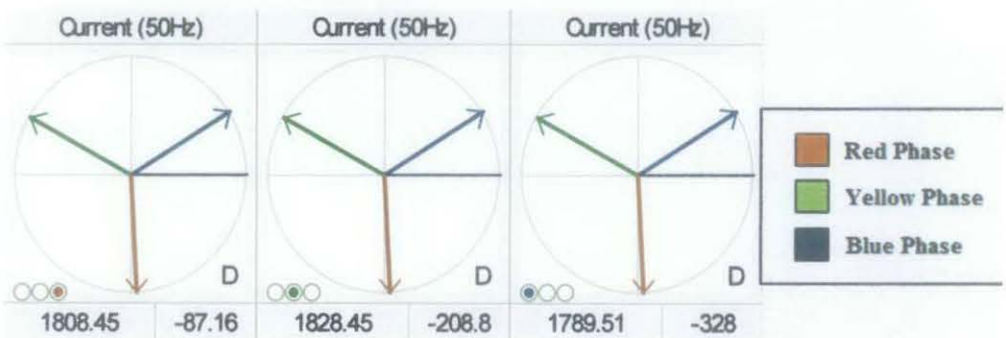



**Figure 22: Fundamental current phase angle diagram of balanced inductive load**

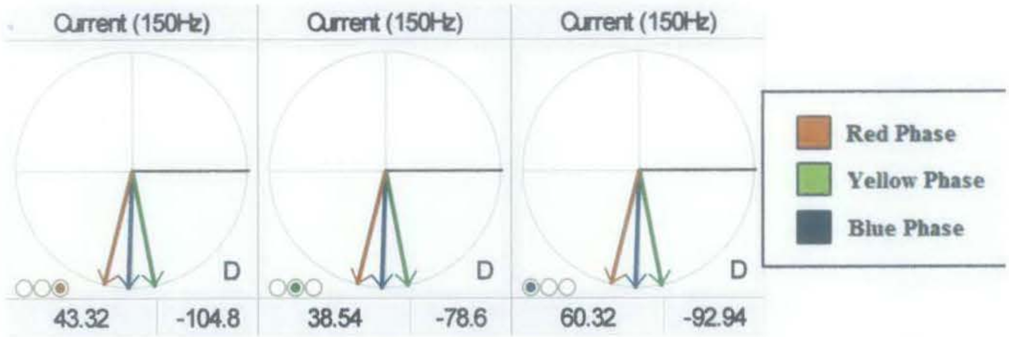



**Figure 23: Third harmonic current phase angle diagram of balanced inductive load**

Table 8 show magnitude of neutral third harmonic reducing as the load impedance is increasing.

**Table 8 - Magnitude of third harmonic neutral current vs. inductive load**

| Load (H) | Neutral Current (mA) |
|---|---|
| ∞ | 0.84 |
| 0.38 | 140.54 |
| 0.51 | 130.09 |
| 0.76 | 87.66 |
| 1.02 | 56.90 |
| 1.53 | 39.35 |

### 4.1.3 Balanced Resistive & Inductive Load

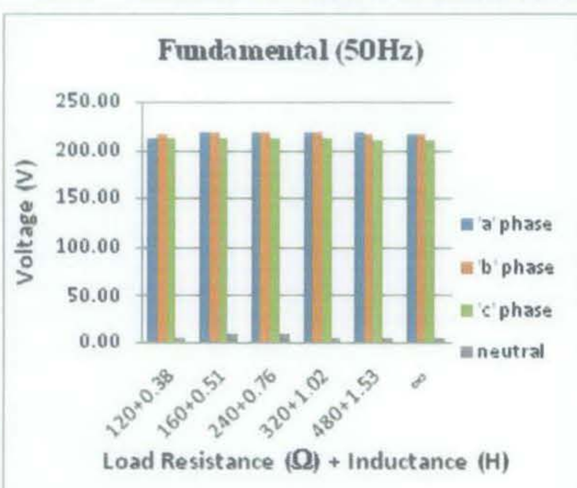



**Figure 24: Fundamental voltage of balanced resistive & inductive load**

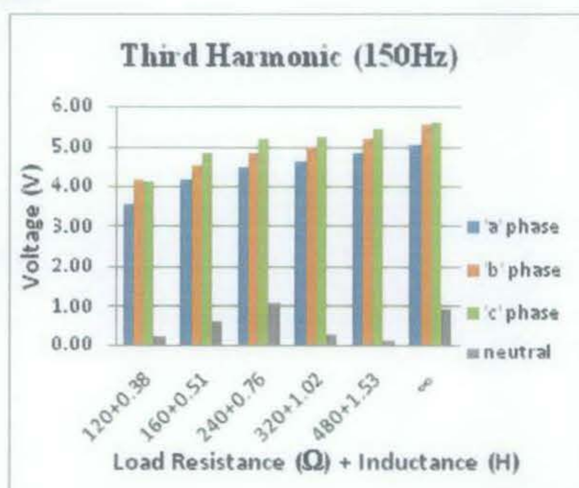



**Figure 25: Third harmonic voltage of balanced resistive & inductive load**

For fundamental frequency in figure 24, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 25, all phases of voltages has different magnitude. As load resistance & inductance increase, magnitude of third harmonic voltage also increases. The highest magnitude of third harmonic voltage is measured when there is no load supplied. The third harmonic voltage has positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with 120 Ohm and 0.38 Henry are used to plot phase angle diagram as in figure 26 and figure 27.

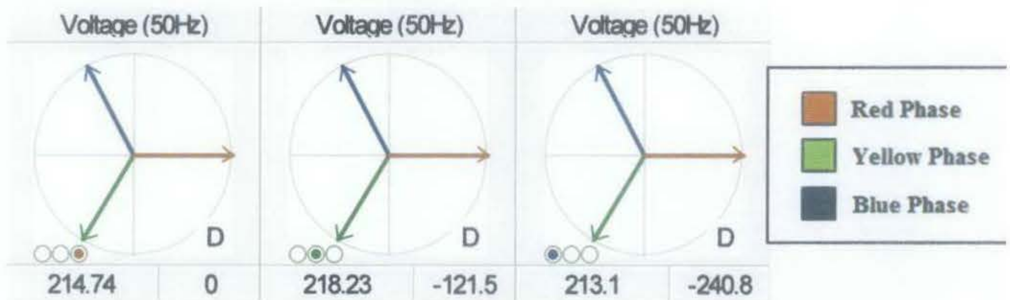



**Figure 26: Fundamental voltage phase angle diagram of balanced resistive & inductive load**

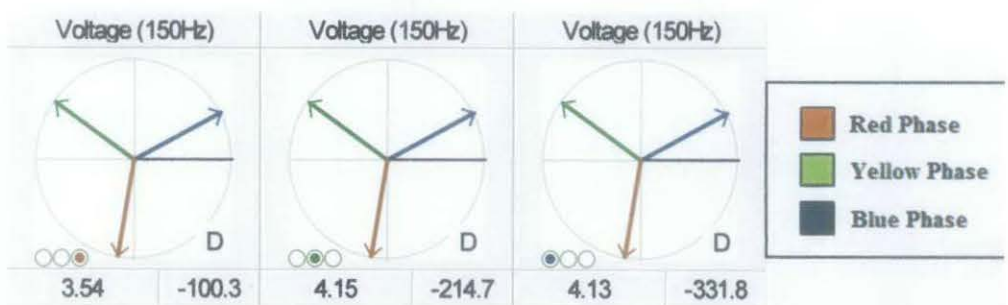



**Figure 27: Third harmonic voltage phase angle diagram of balanced resistive & inductive load**

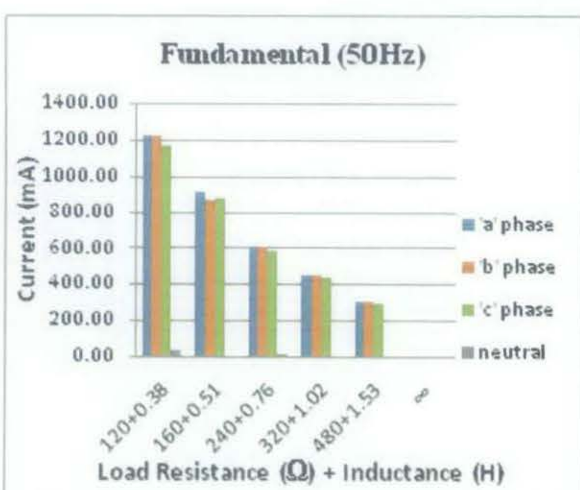



**Figure 28: Fundamental current of balanced resistive & inductive load**

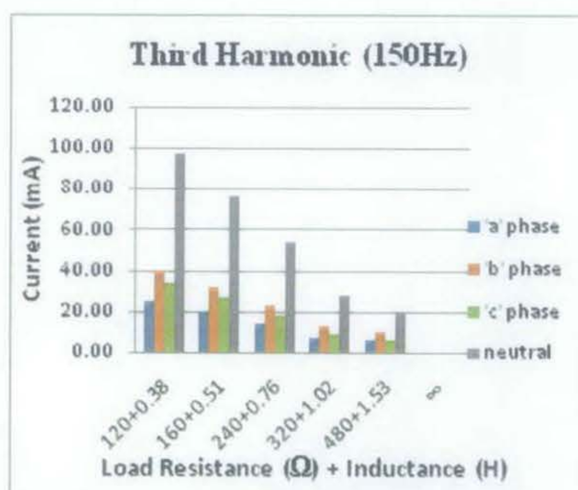



**Figure 29: Third harmonic current of balanced resistive & inductive load**

For fundamental frequency in figure 28, magnitude of all phases of current is approximately same while for current of third harmonic in figure 29, all phases are different. There is almost no neutral current for fundamental frequency. The magnitude of phase and neutral current for third harmonic frequency is decreasing as the load impedance is increasing. The neutral third harmonic current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with 120 Ohm and 0.38 Henry are used to plot phase angle diagram as in figure 30 and figure 31.

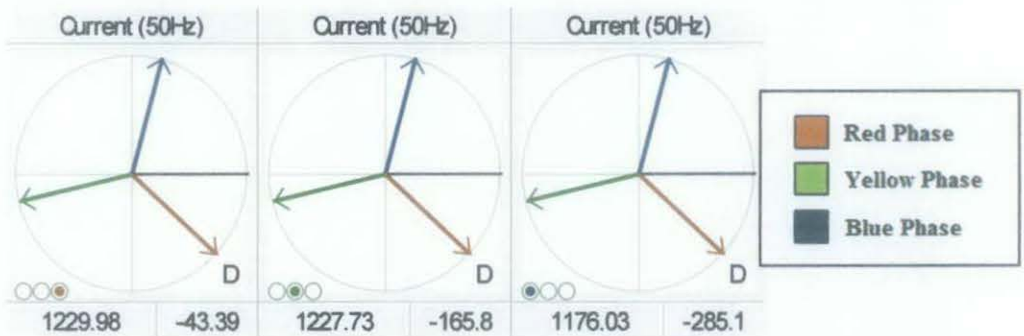



**Figure 30: Fundamental current phase angle diagram of balanced resistive & inductive load**

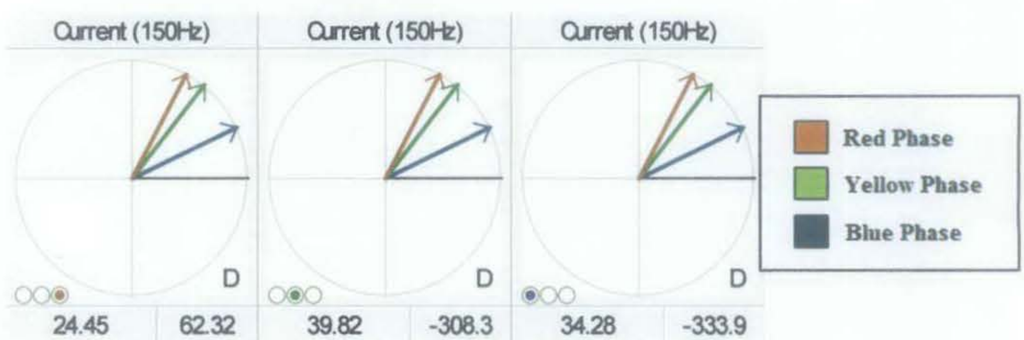



**Figure 31: Third harmonic current phase angle diagram of balanced resistive & inductive load**

Table 9 show the magnitude of third harmonic current reducing as load impedance is increasing.

**Table 9 - Magnitude of third harmonic neutral current vs. resistive + inductive load**

| Load ($\Omega$ + H) | Neutral Current (mA) |
|---|---|
| $\infty$ | 0.84 |
| 120 + 0.38 | 97.06 |
| 160 + 0.51 | 76.63 |
| 240 + 0.76 | 54.35 |
| 320 + 1.02 | 28.48 |
| 480 + 1.53 | 20.73 |

## 4.2 Generator NER

### 4.2.1 Balanced Resistive Load

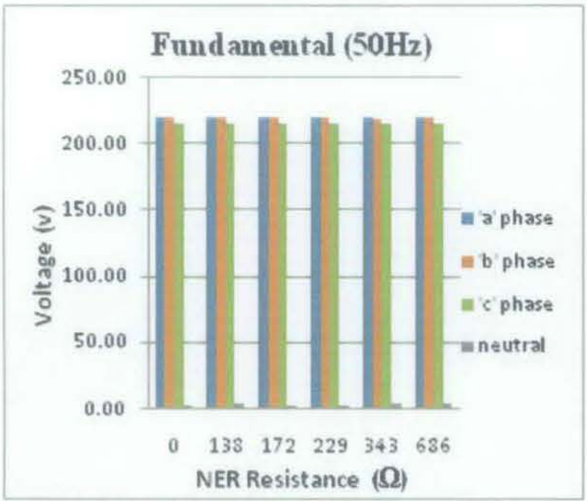



**Figure 32: Fundamental voltage of balanced resistive load with NER**

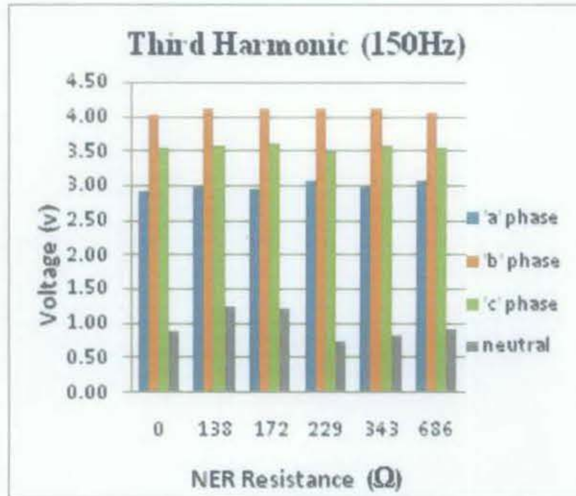



**Figure 33: Third harmonic voltage of balanced resistive load with NER**

For fundamental frequency in figure 32, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 33, all phases of voltages has different magnitude. As NER resistance increase, magnitude of fundamental & third harmonic voltage stays almost same. The third harmonic voltage has positive sequence of phase angle. Example of phase angle data for fundamental & third harmonic current with NER resistance of 138 Ohm are used to plot phase angle diagram as figure 34 and figure 35.

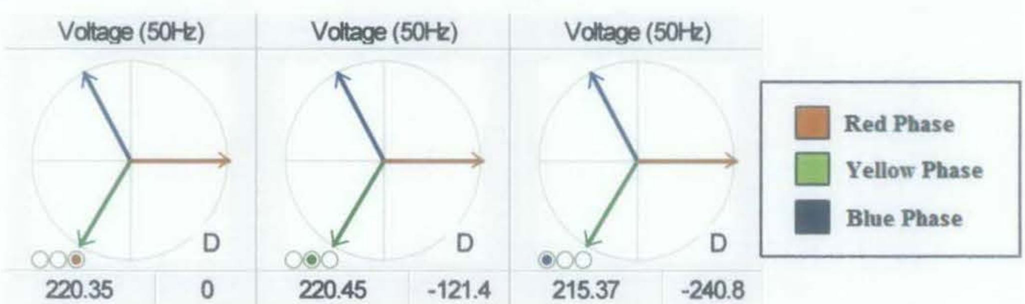



**Figure 34: Fundamental voltage phase angle diagram of balanced resistive load with NER**

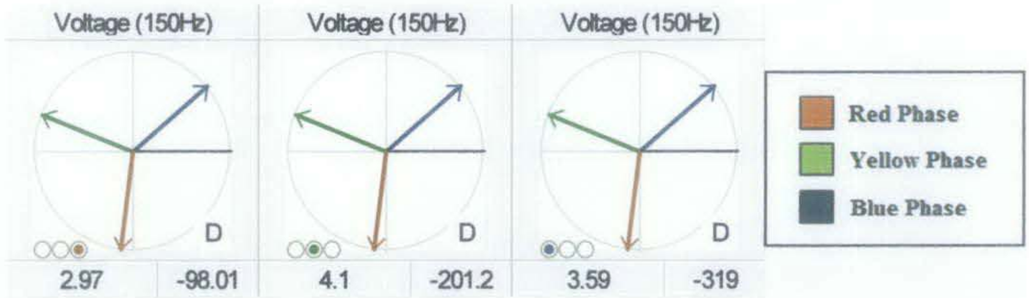



**Figure 35: Third harmonic voltage phase angle diagram of balanced resistive load with NER**

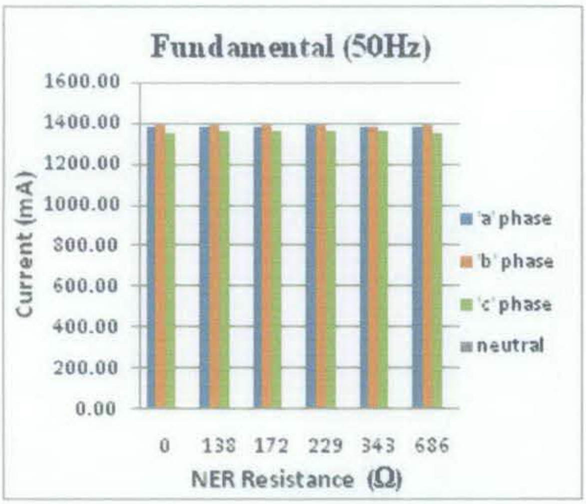



**Figure 36: Fundamental current of balanced resistive load with NER**

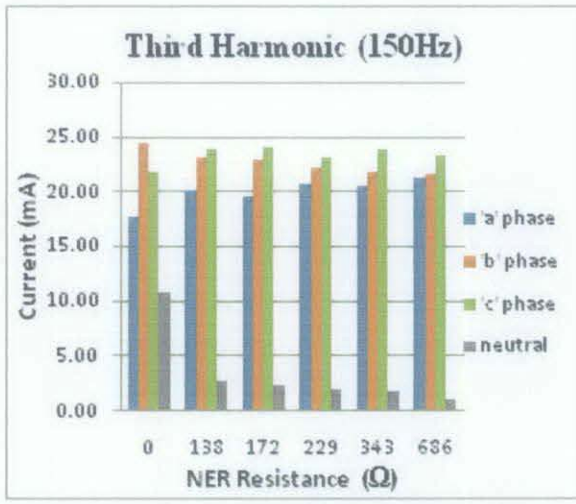



**Figure 37: Third harmonic current of balanced resistive load with NER**

For fundamental frequency in figure 36, magnitude of all phases of current is approximately same while for current of third harmonic in figure 37, all phases are different. There is almost no neutral current for fundamental frequency. The magnitude of neutral current for third harmonic frequency is decreasing as the NER resistance is increasing. The highest neutral third harmonic current is measured when there is no NER being connected. The third harmonic current are not three times the phase current due to positive sequence of phase angle. Example of phase angle data for fundamental & third harmonic current with NER resistance of 138 Ohm are used to plot phase angle diagram as in figure 38 and figure 39.

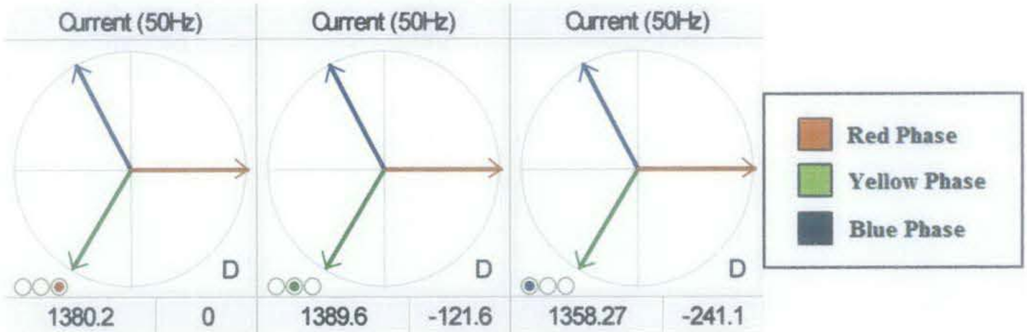



**Figure 38: Fundamental current phase angle diagram of balanced resistive load with NER**

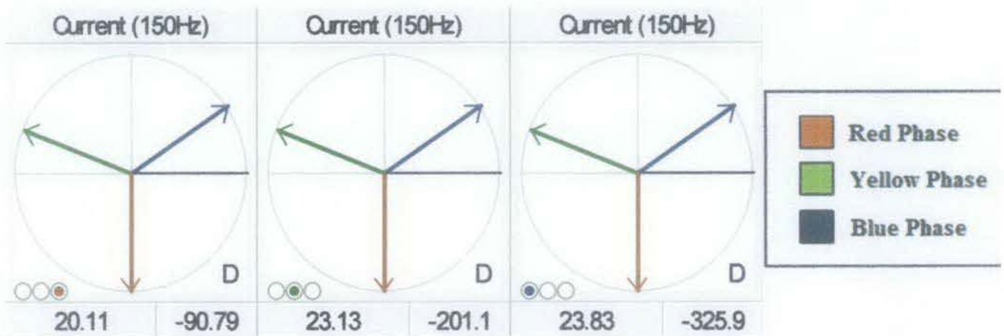



**Figure 39: Third harmonic current phase angle diagram of balanced resistive load with NER**

Table 10 shows the percentage of reduction between each NER increment.

**Table 10 – Percentage of reduction for balanced resistive load vs. NER**

| **NER** (Ω) | **Neutral Current** (mA) | **Percentage of Reduction** (%) |
|---|---|---|
| 0 | 10.90 | 0.00 |
| 138 | 2.75 | 74.72 |
| 172 | 2.44 | 77.57 |
| 229 | 2.11 | 80.61 |
| 343 | 1.77 | 83.72 |
| 686 | 1.07 | 90.18 |

### 4.2.2 Balanced Inductive Load

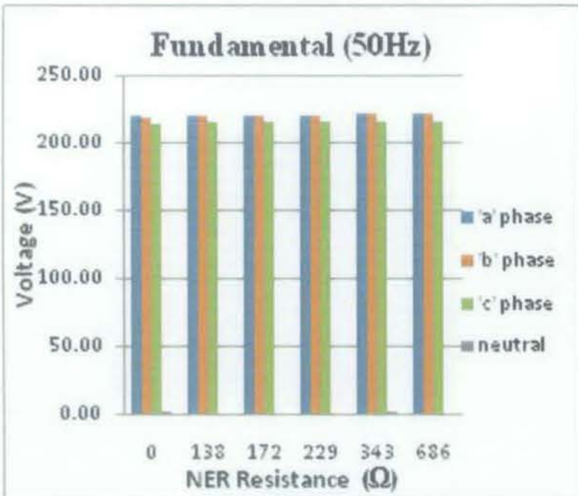



**Figure 40: Fundamental voltage of balanced inductive load with NER**

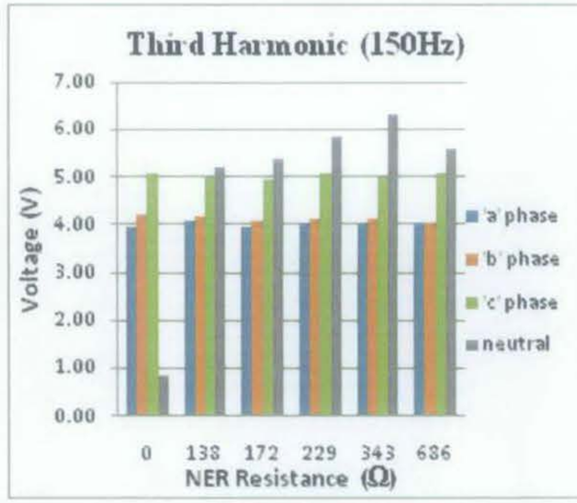



**Figure 41: Third harmonic voltage of balanced inductive load with NER**

For fundamental frequency in figure 40, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 41, all phases of voltages has different magnitude. As NER resistance increase, magnitude of fundamental & third harmonic voltage stays almost same except for neutral phase voltage. The lowest third harmonic neutral phase voltage is measured when there is no NER connected. The third harmonic voltage has zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with NER resistance of 138 Ohm are used to plot phase angle diagram as in figure 42 and figure 43.

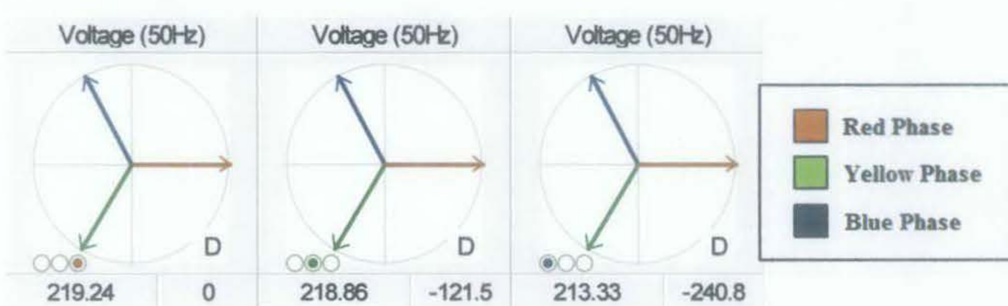



**Figure 42: Fundamental voltage phase angle diagram of balanced inductive load with NER**

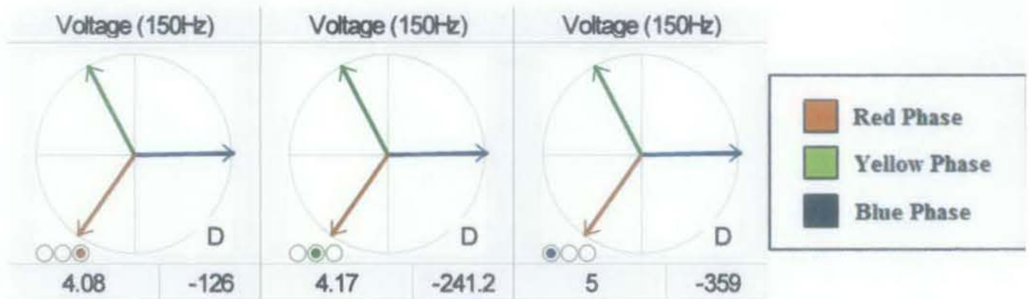



**Figure 43: Third harmonic voltage phase angle diagram of balanced inductive load with NER**

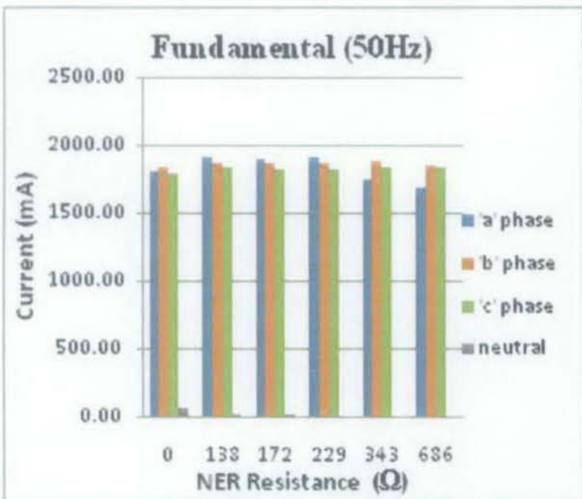



**Figure 44: Fundamental current of balanced inductive load with NER**

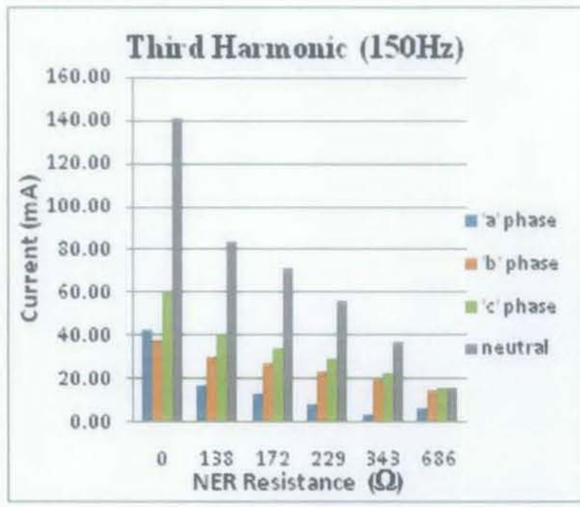



**Figure 45: Third harmonic current of balanced inductive load with NER**

For fundamental frequency in figure 44, magnitude of all phases of current is approximately same while for current of third harmonic in figure 45, all phases are different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the NER resistance is increasing. The highest neutral third harmonic current is measured when there is no NER being connected. The third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with NER resistance of 138 ohm are used to plot phase angle diagram as in figure 46 and figure 47.

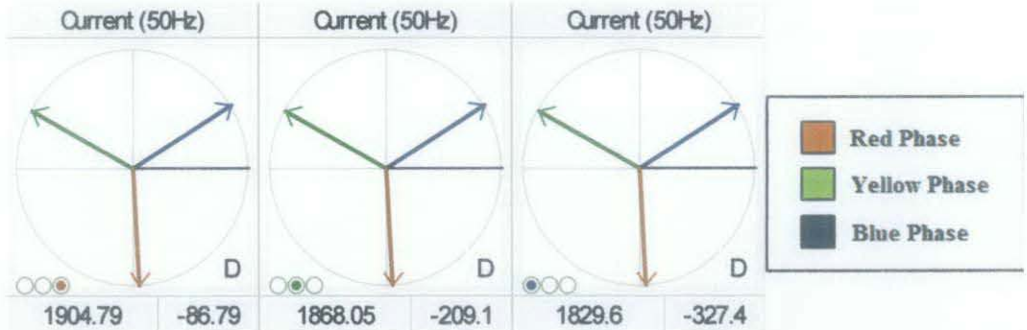



**Figure 46: Fundamental current phase angle diagram of balanced inductive load with NER**

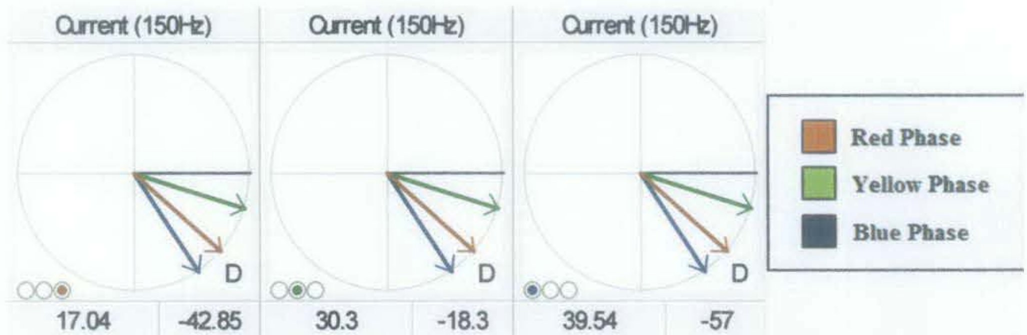



**Figure 47: Third harmonic current phase angle diagram of balanced inductive load with NER**

Table 11 shows the percentage of reduction between each NER increment.

**Table 11 - Percentage of reduction for balanced inductive load vs. NER**

| **NER** (Ω) | **Neutral Current** (mA) | **Percentage of Reduction** (%) |
|---|---|---|
| 0 | 140.54 | 0.00 |
| 138 | 83.33 | 40.70 |
| 172 | 71.07 | 49.43 |
| 229 | 55.82 | 60.28 |
| 343 | 37.39 | 73.40 |
| 686 | 16.44 | 88.30 |

### 4.2.3 Balanced Resistive & Inductive Load

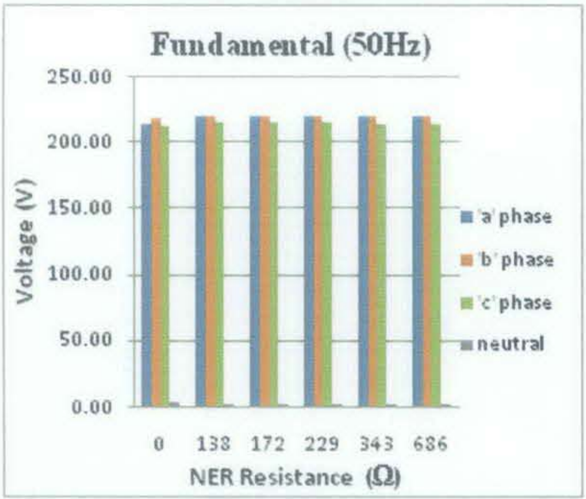



**Figure 48: Fundamental voltage of balanced resistive & inductive load with NER**

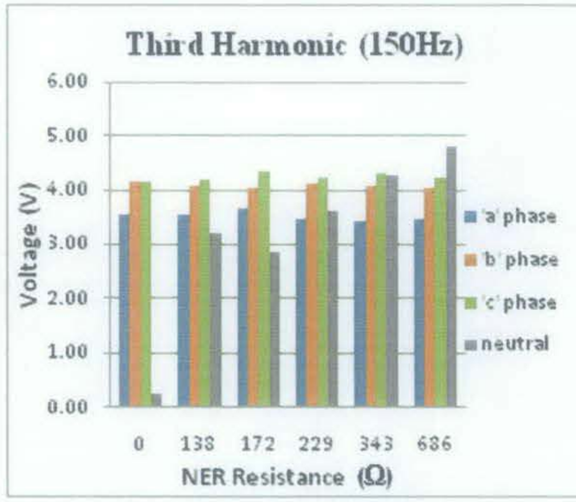



**Figure 49: Third harmonic voltage of balanced resistive & inductive load with NER**

For fundamental frequency in figure 48, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 49, all phases of voltages has different magnitude. As NER resistance increase, magnitude of fundamental & third harmonic voltage stays almost same except for third harmonic neutral phase voltage. The lowest third harmonic neutral phase voltage is measured when there is no NER connected. The third harmonic voltage has positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with NER resistance of 138 Ohm are used to plot phase angle diagram as in figure 50 and figure 51.


**Figure 50: Fundamental voltage phase angle diagram of balanced resistive & inductive load with NER**

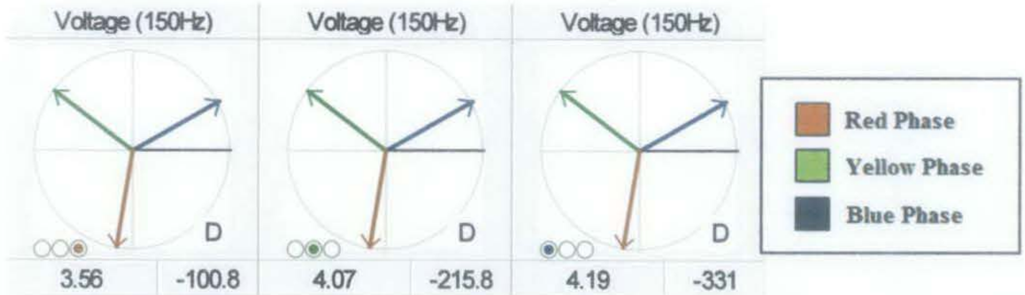



**Figure 51: Third harmonic voltage phase angle diagram of balanced resistive & inductive load with NER**

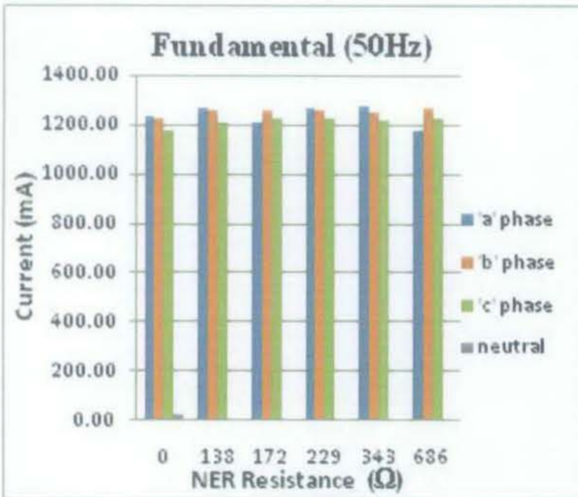



**Figure 52: Fundamental current of balanced resistive & inductive load with NER**

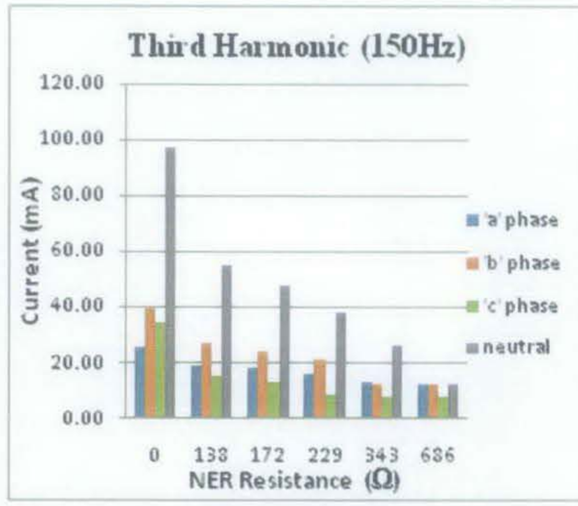



**Figure 53: Third harmonic current of balanced resistive & inductive load with NER**

For fundamental frequency in figure 52, magnitude of all phases of current is approximately same while for current of third harmonic in figure 53 all phases are different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the NER resistance is increasing. The highest neutral third harmonic current is measured when there is no NER being connected. The neutral third harmonic current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with NER resistance of 138 Ohm are used to plot phase angle diagram as in figure 54 and figure 55.

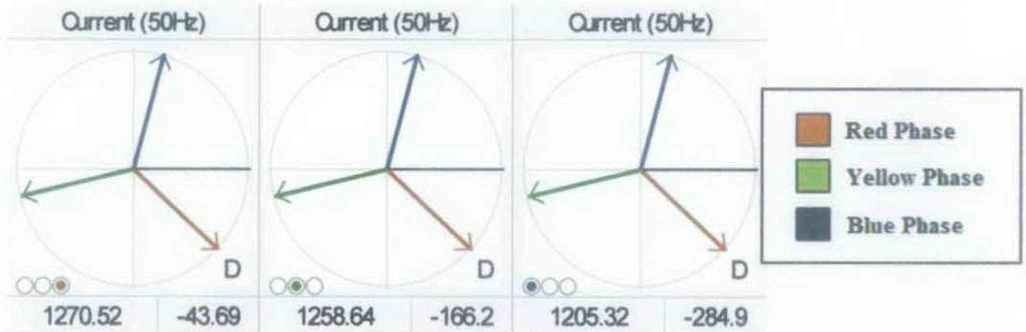



**Figure 54: Fundamental current phase angle diagram of balanced resistive & inductive load with NER**

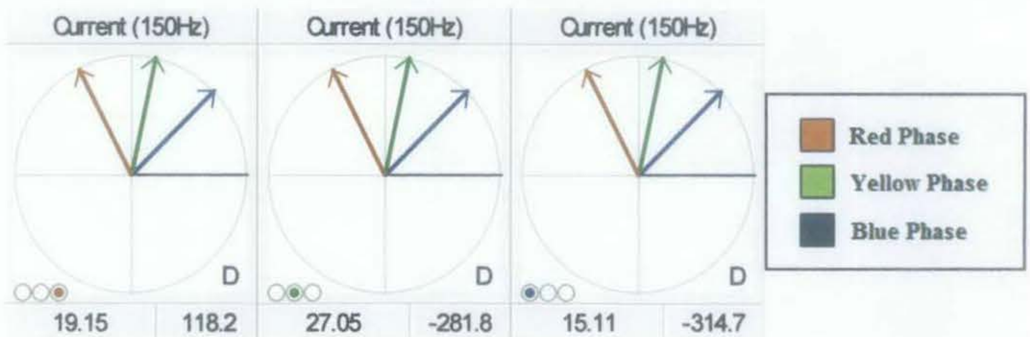



**Figure 55: Third harmonic phase angle diagram of balanced resistive & inductive load with NER**

Table 12 shows the percentage of reduction between each NER increment.

**Table 12 - Percentage of reduction for balanced resistive & inductive load vs. NER**

| NER (Ω) | Neutral Current (mA) | Percentage of Reduction (%) |
|---|---|---|
| 0 | 97.06 | 0.00 |
| 138 | 55.06 | 43.28 |
| 172 | 47.54 | 51.02 |
| 229 | 38.12 | 60.73 |
| 343 | 26.40 | 72.80 |
| 686 | 12.20 | 87.43 |

### 4.3 Generator with Tuned Peterson Coil

#### 4.3.1 Balanced Resistive Load


**Figure 56: Fundamental voltage of balanced resistive load with tuned Peterson coil**

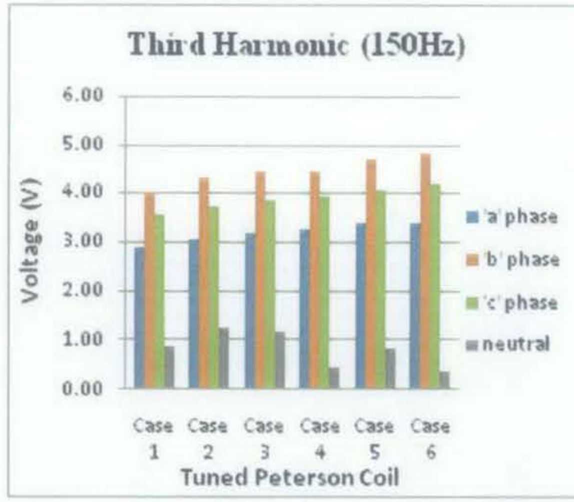



**Figure 57: Third harmonic voltage of balanced resistive load with tuned Peterson coil**

Table 13 show description of Case 1,2,3,4,5 and 6:

**Table 13 – Description of Tuned Peterson Coil for balanced resistive load**

| Case | Tuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H + 1.33μF |
| Case 3 | 172Ω + 5.08H + 1.99μF |
| Case 4 | 229Ω + 3.8H + 2.65μF |
| Case 5 | 343Ω + 2.53H + 3.98μF |
| Case 6 | 686Ω + 1.69H + 4.64μF |

For fundamental frequency in figure 56, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 57, all phases of voltages has different magnitude. As Tuned Peterson Coil resistance and reactance increase, magnitude of third harmonic voltage also increases. The third harmonic voltage has positive sequence of phase angle.. Example of phase angle data for fundamental and third harmonic voltage with Tuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 58 and figure 59.

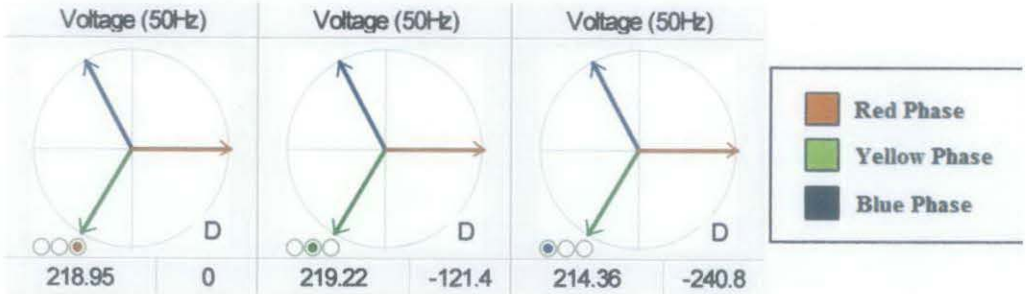
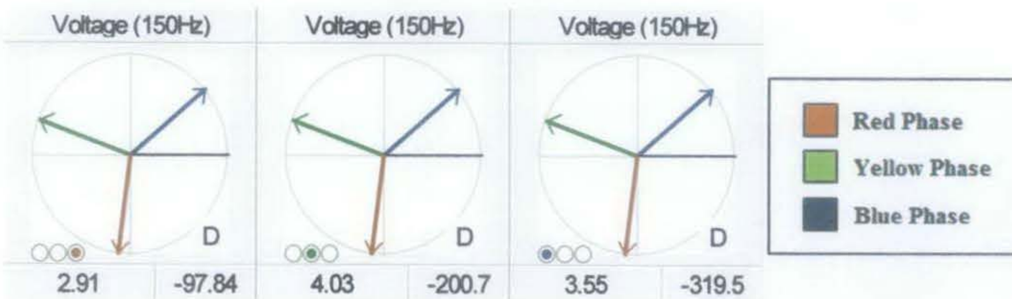



**Figure 58: Fundamental voltage phase angle diagram of balanced resistive load with tuned Peterson coil**



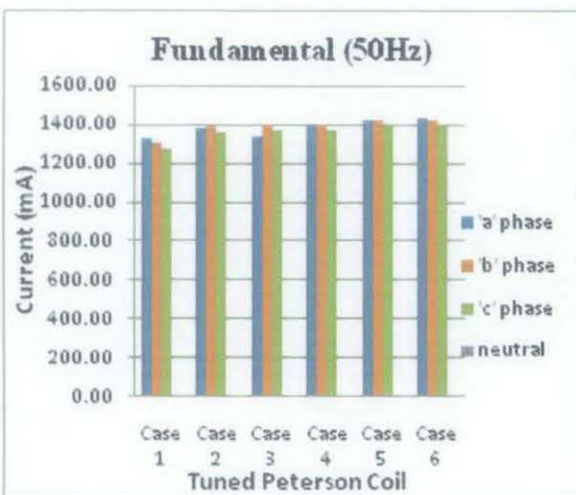




**Figure 59: Third harmonic voltage phase angle diagram of balanced resistive load with tuned Peterson coil**

**Figure 60: Fundamental current of balanced resistive load with tuned Peterson coil**

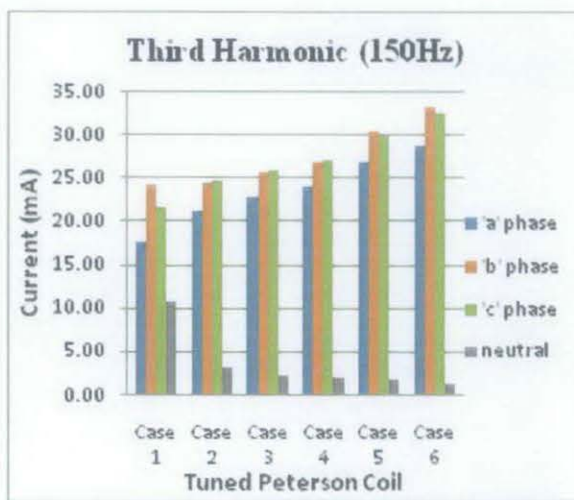



**Figure 61: Third harmonic current of balanced resistive load with tuned Peterson coil**

For fundamental frequency in figure 60, magnitude of all phases of current is approximately same except for case 1 which the magnitude of phase current is slightly lower while for all third harmonic current phases in figure 61, the magnitude are different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the Tuned Peterson Coil resistance and reactance is increasing. The highest neutral third harmonic current is measured when there is no Tuned Peterson Coil being connected. The fundamental and third harmonic neutral current are not three times the phase current due to positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Tuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 62 and figure 63.

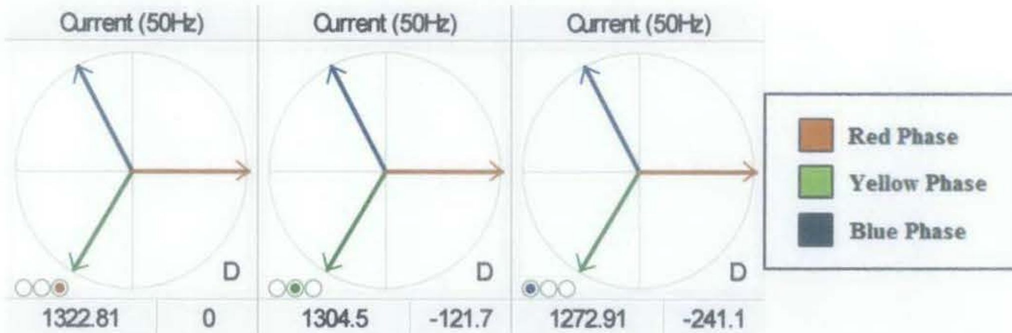



**Figure 62: Fundamental current phase angle diagram of balanced resistive load with tuned Peterson coil**

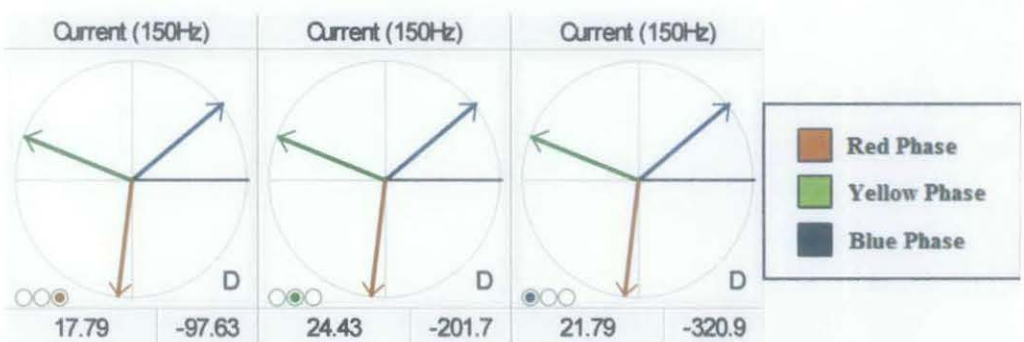



**Figure 63: Third harmonic current phase angle diagram of balanced resistive load with tuned Peterson coil**

Table 14 shows the percentage of reduction between each Tuned Peterson Coil increment.

**Table 14 - Percentage of reduction for balanced resistive load vs. Tuned Peterson Coil**

| **Case** | **Tuned Peterson Coil** | **Neutral Current** (mA) | **Percentage of Reduction** (%) |
|---|---|---|---|
| Case 1 | 0 | 10.90 | 0.00 |
| Case 2 | 138Ω + 7.6H + 1.33μF | 3.31 | 69.64 |
| Case 3 | 172Ω + 5.08H + 1.99μF | 2.32 | 78.72 |
| Case 4 | 229Ω + 3.8H + 2.65μF | 2.13 | 80.46 |
| Case 5 | 343Ω + 2.53H + 3.98μF | 1.93 | 82.29 |
| Case 6 | 686Ω + 169H + 4.64μF | 1.37 | 87.43 |

### 4.3.2 Balanced Inductive Load

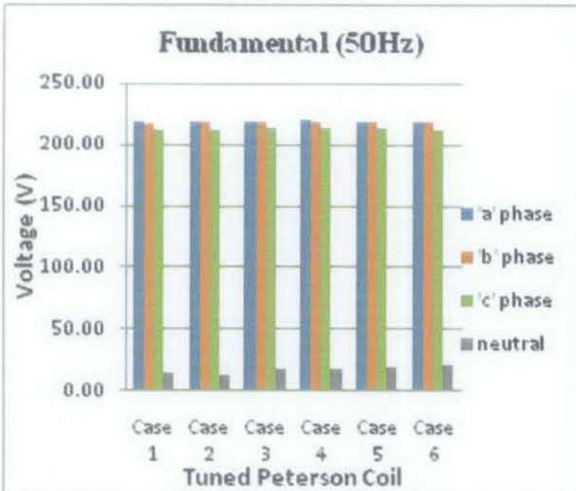



**Figure 64: Fundamental voltage of balanced inductive load with tuned Peterson coil**

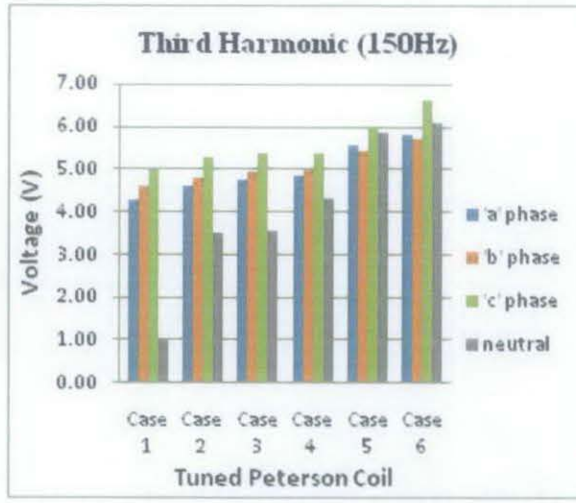



**Figure 65: Third harmonic voltage of balanced inductive load with tuned Peterson coil**

Table 15 show description of Case 1,2,3,4,5 and 6:

**Table 15 – Description of Tuned Peterson Coil for balanced inductive load**

| Case | Tuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H + 1.33μF |
| Case 3 | 172Ω + 5.08H + 1.99μF |
| Case 4 | 229Ω + 3.8H + 2.65μF |
| Case 5 | 343Ω + 2.53H + 3.98μF |
| Case 6 | 686Ω + 169H + 4.64μF |

For fundamental frequency in figure 64, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 65, all phases of voltages has different magnitude. As Tuned Peterson Coil increase, magnitude of third harmonic voltage also increases. The third harmonic voltage has positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with Tuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 66 and figure 67.

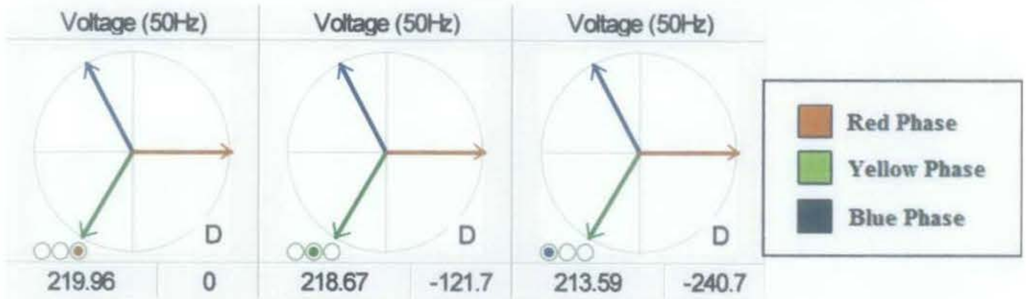



**Figure 66: Fundamental voltage phase angle diagram of balanced inductive load with tuned Peterson coil**


**Figure 67: Third harmonic voltage phase angle diagram of balanced inductive load with tuned Peterson coil**

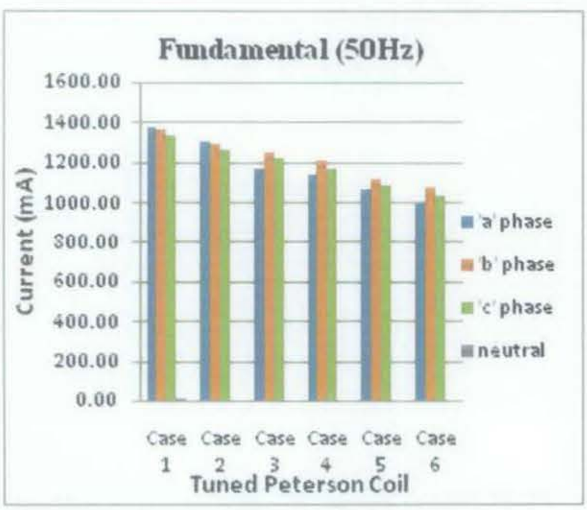



**Figure 68: Fundamental current of balanced inductive load with tuned Peterson coil**

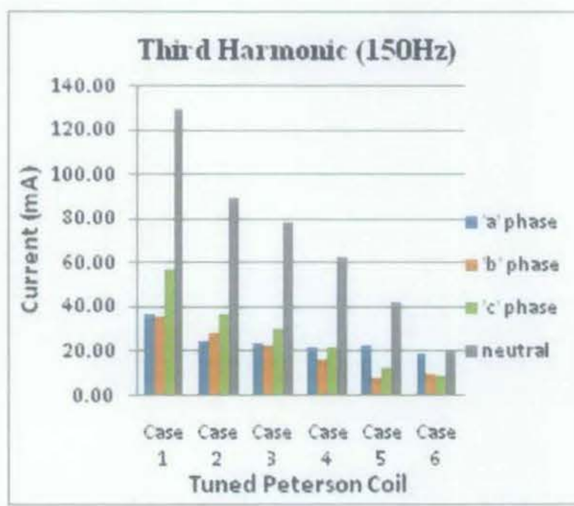



**Figure 69: Third harmonic current of balanced inductive load with tuned Peterson coil**

For fundamental frequency in figure 68, magnitude of all phases of current is approximately same while for all third harmonic current phases in figure 69, the magnitude are different. The magnitude of fundamental and third harmonic frequency current is decreasing as Tuned Peterson Coil resistance and reactance increasing. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the Tuned Peterson Coil resistance and reactance is increasing. The highest neutral third harmonic current is measured when there is no Tuned Peterson Coil (case 1) being connected. The neutral third harmonic current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Tuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 70 and figure 71.

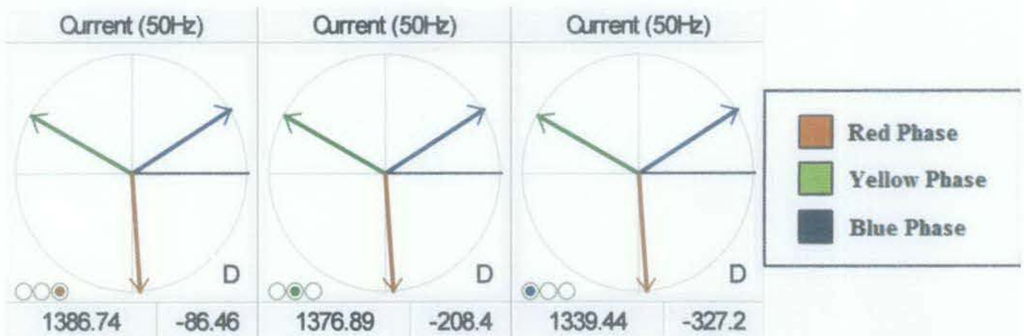



**Figure 70: Fundamental current phase angle diagram of balanced inductive load with tuned Peterson coil**

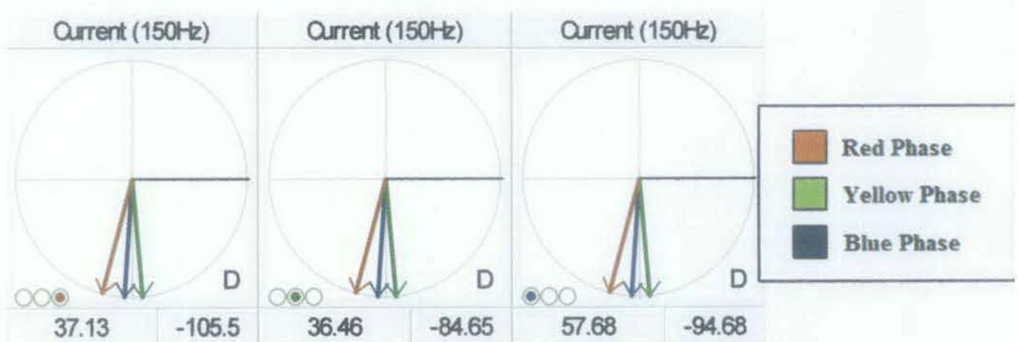



**Figure 71: Third harmonic current phase angle diagram of balanced inductive load with tuned Peterson coil**

Table 16 shows the percentage of reduction between each Tuned Peterson Coil increment.

**Table 16 - Percentage of reduction for balanced inductive load vs. Tuned Peterson Coil**

| **Case** | **Tuned Peterson Coil** | **Neutral Current** (mA) | **Percentage of Reduction** (%) |
|---|---|---|---|
| Case 1 | 0 | 130.09 | 0.00 |
| Case 2 | 138Ω + 7.6H + 1.33μF | 89.82 | 30.96 |
| Case 3 | 172Ω + 5.08H + 1.99μF | 78.75 | 39.46 |
| Case 4 | 229Ω + 3.8H + 2.65μF | 63.34 | 51.31 |
| Case 5 | 343Ω + 2.53H + 3.98μF | 42.81 | 67.10 |
| Case 6 | 686Ω + 169H + 4.64μF | 21.16 | 83.74 |

### 4.3.3 Balanced Resistive & Inductive Load

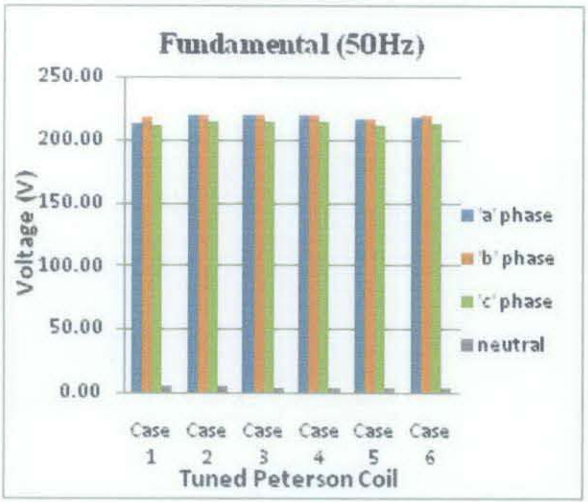



**Figure 72: Fundamental voltage of balanced resistive & inductive load with tuned Peterson coil**

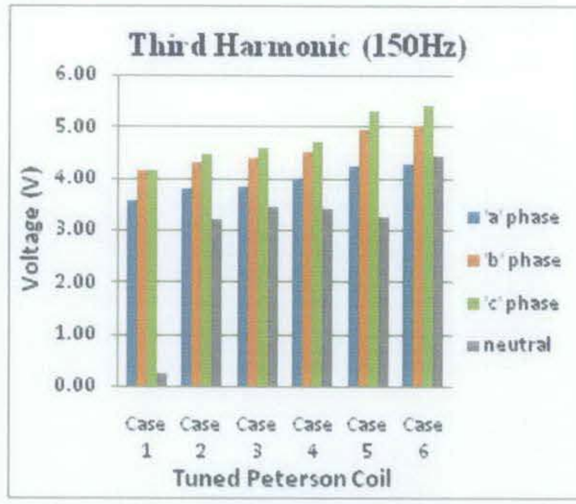



**Figure 73: Third harmonic voltage of balanced resistive & inductive load with tuned Peterson coil**

Table 17 show description of Case 1,2,3,4,5 and 6:

**Table 17 – Description of Tuned Peterson Coil for resistive & Inductive load**

| Case | Tuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H + 1.33μF |
| Case 3 | 172Ω + 5.08H + 1.99μF |
| Case 4 | 229Ω + 3.8H + 2.65μF |
| Case 5 | 343Ω + 2.53H + 3.98μF |
| Case 6 | 686Ω + 169H + 4.64μF |

For fundamental frequency in figure 72, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 73, all phases of voltages has different magnitude. As Tuned Peterson Coil resistance and reactance increase, magnitude of third harmonic voltage also increases. The third harmonic voltage has positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Tuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 74 and figure 75.

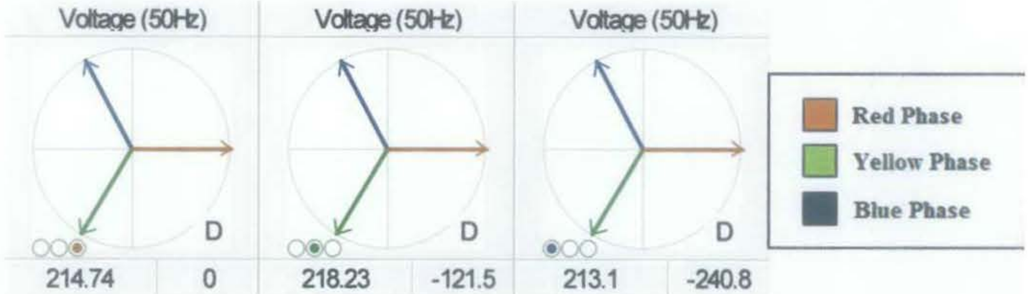



**Figure 74: Fundamental voltage phase angle diagram of balanced resistive & inductive load with tuned Peterson coil**

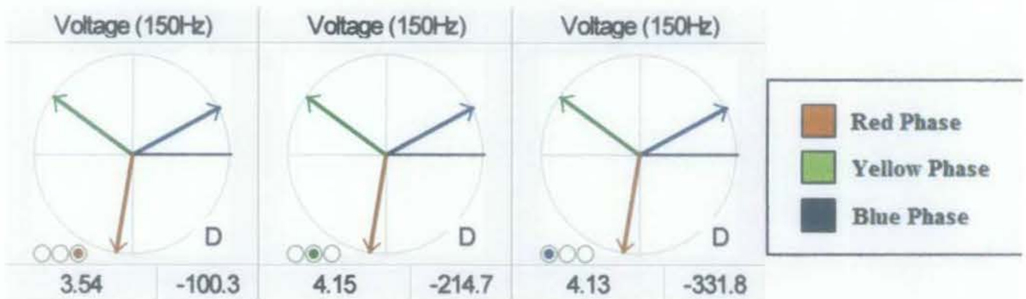
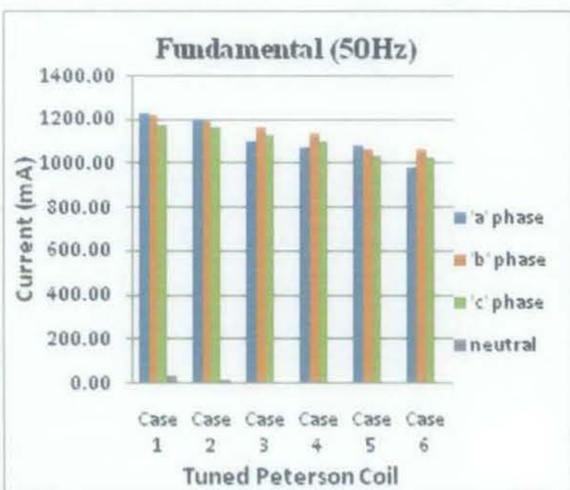



**Figure 75: Third harmonic voltage phase angle diagram of balanced resistive & inductive load with tuned Peterson coil**



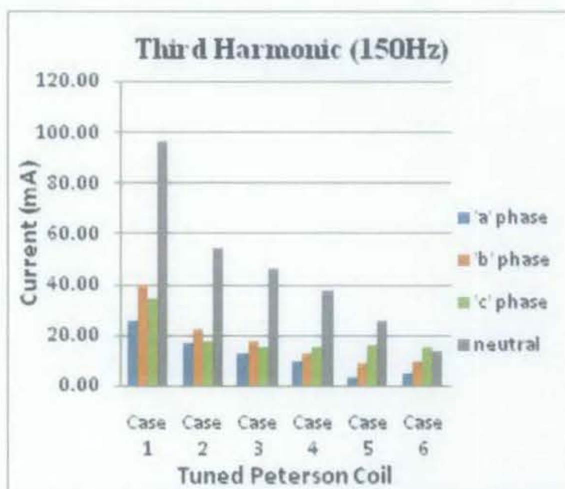




**Figure 76: Fundamental current of balanced resistive & inductive load with tuned Peterson coil**

**Figure 77: Third harmonic current of balanced resistive & inductive load with tuned Peterson coil**

For fundamental frequency in figure 76, magnitude of all phases of current is approximately same while for all third harmonic current phases in figure 77, the magnitude are different. The magnitude of fundamental and third harmonic frequency current is decreasing as Tuned Peterson Coil resistance and reactance increasing. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the Tuned Peterson Coil resistance and reactance is increasing. The highest neutral third harmonic current is measured when there is no Tuned Peterson Coil (case 1) being connected. The neutral third harmonic current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Tuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 78 and figure 79.

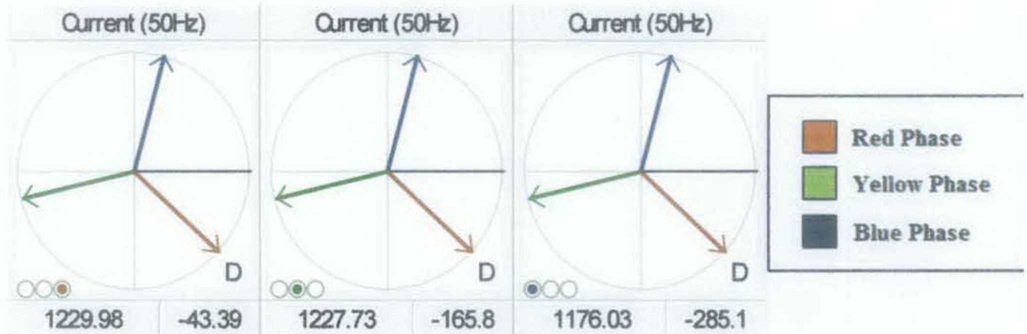



**Figure 78: Fundamental current phase angle diagram of balanced resistive & inductive load with tuned Peterson coil**

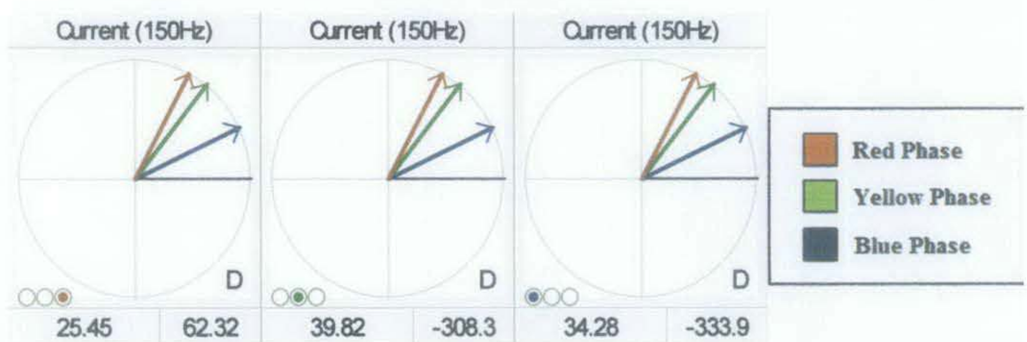



**Figure 79: Third harmonic current phase angle diagram of balanced resistive & inductive load with tuned Peterson coil**

Table 18 shows the percentage of reduction between each Tuned Peterson Coil increment.

**Table 18 - Percentage of reduction for balanced resistive & inductive load vs. Tuned Peterson Coil**

| **Case** | **Tuned Peterson Coil** | **Neutral Current** (mA) | **Percentage of Reduction** (%) |
|---|---|---|---|
| Case 1 | 0 | 97.06 | 0.00 |
| Case 2 | 138Ω + 7.6H + 1.33μF | 54.48 | 43.88 |
| Case 3 | 172Ω + 5.08H + 1.99μF | 46.70 | 51.89 |
| Case 4 | 229Ω + 3.8H + 2.65μF | 37.41 | 61.46 |
| Case 5 | 343Ω + 2.53H + 3.98μF | 25.92 | 73.30 |
| Case 6 | 686Ω + 169H + 4.64μF | 13.21 | 86.39 |

## 4.4 Generator with Untuned Peterson Coil

### 4.4.1 Balanced Resistive Load

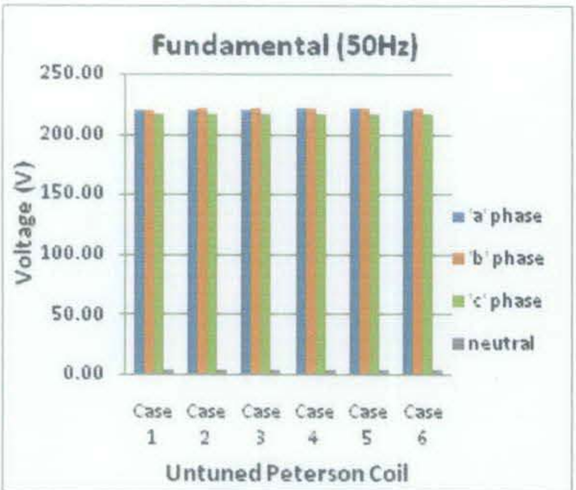



**Figure 80: Fundamental voltage of balanced resistive load with untuned Peterson coil**

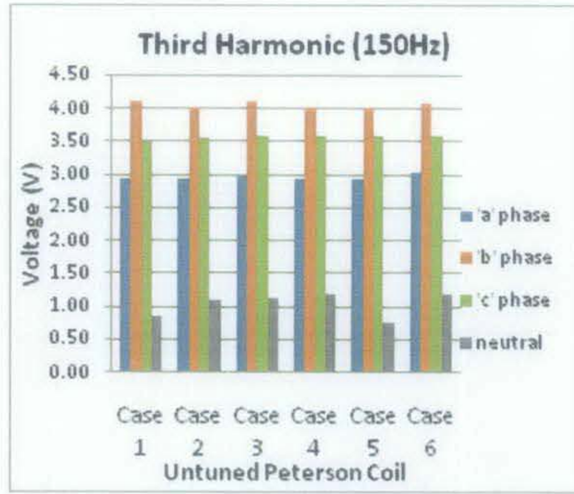



**Figure 81: Third harmonic voltage of balanced resistive load with untuned Peterson coil**

Table 19 show the description of case 1,2,3,4,5 and 6:

**Table 19 - Description of Untuned Peterson Coil for balanced resistive load**

| Case | Untuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H |
| Case 3 | 172Ω + 5.08H |
| Case 4 | 229Ω + 3.8H |
| Case 5 | 343Ω + 2.53H |
| Case 6 | 686Ω + 169H |

For fundamental frequency in figure 80, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 81, all phases of voltages has different magnitude. As Untuned Peterson Coil resistance and reactance increase, magnitude of fundamental and third harmonic voltage remains same. The third harmonic voltage has positive sequence of phase angle.. Example of phase angle data for fundamental and third harmonic voltage with Untuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 82 and figure 83.

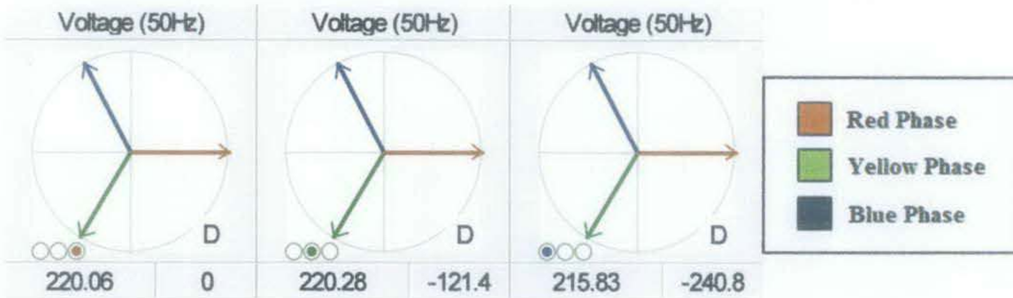



**Figure 82: Fundamental voltage phase angle diagram of balanced resistive load with untuned Peterson coil**

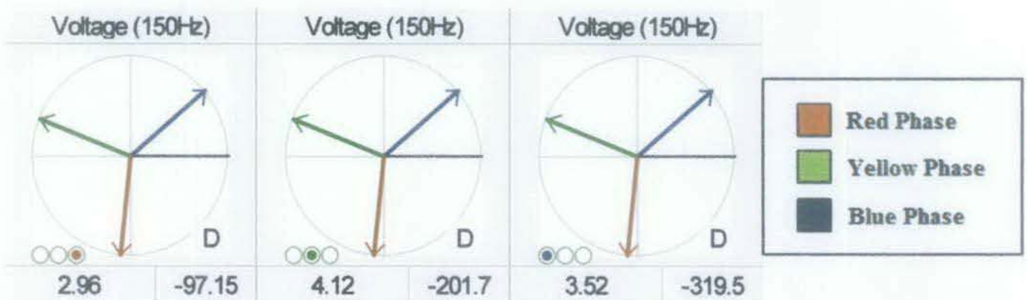



**Figure 83: Third harmonic voltage phase angle diagram of balanced resistive load with untuned Peterson coil**


**Figure 84: Fundamental current of balanced resistive load with untuned Peterson coil**

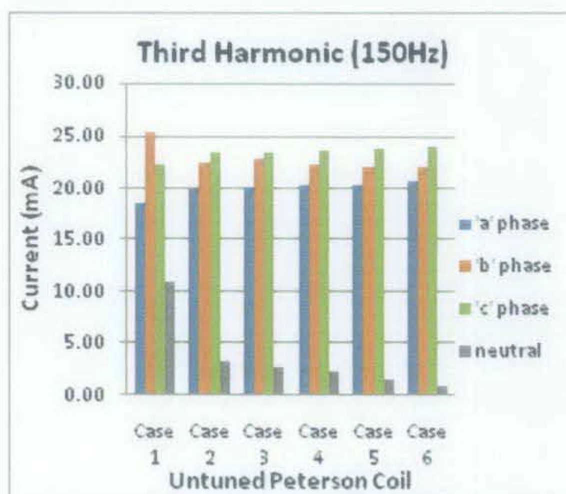



**Figure 85: Third harmonic current of balanced resistive load with untuned Peterson coil**

Table 20 show the description of case 1,2,3,4,5 and 6:

**Table 20 - Description of Untuned Peterson Coil for balanced resistive load**

| Case | Untuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H |

| | |
|---|---|
| Case 3 | 172Ω + 5.08H |
| Case 4 | 229Ω + 3.8H |
| Case 5 | 343Ω + 2.53H |
| Case 6 | 686Ω + 169H |

For fundamental frequency in figure 84, magnitude of all phases of current is approximately same except for case 5 which the magnitude of red phase current is slightly lower while for all third harmonic current phases in figure 85, the magnitude are different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the Untuned Peterson Coil resistance and reactance is increasing. The highest neutral third harmonic current is measured when there is no Tuned Peterson Coil being connected. The third harmonic neutral current are not three times the phase current due to positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Untuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 86 and figure 87.

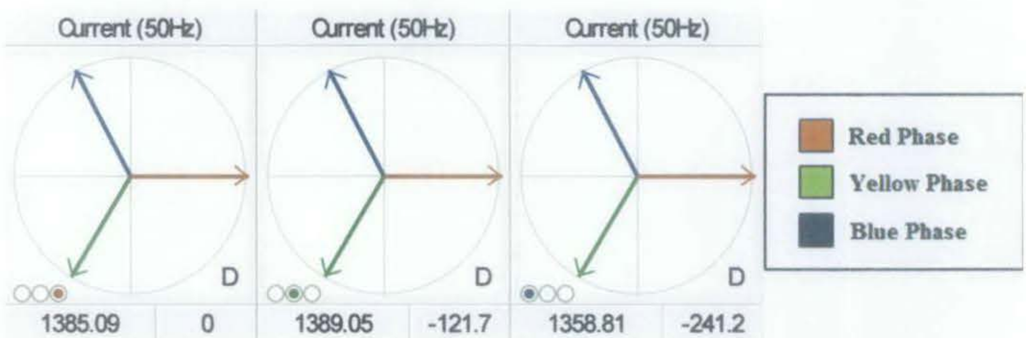



**Figure 86: Fundamental current phase angle diagram of balanced resistive load with untuned Peterson coil**

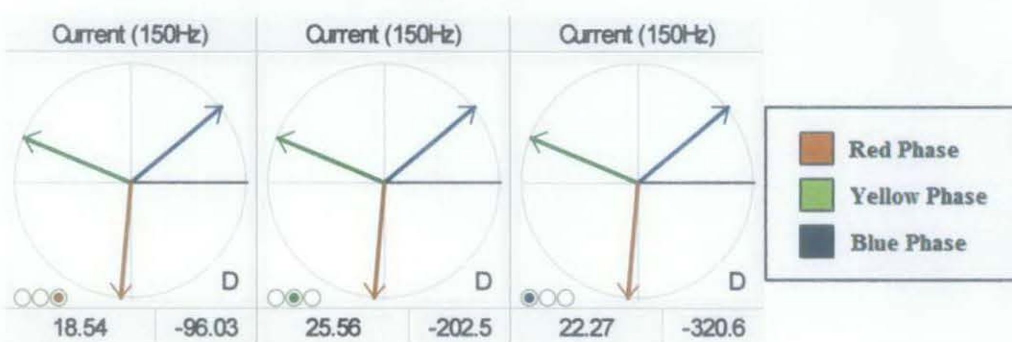



**Figure 87: Third harmonic current phase angle diagram of balanced resistive load with untuned Peterson coil**

Table 21 shows the percentage of reduction between each Untuned Peterson Coil increment

**Table 21 - Percentage of reduction for balanced resistive load vs. Untuned Peterson Coil**

| Case | Tuned Peterson Coil | Neutral Current (mA) | Percentage of Reduction (%) |
|---|---|---|---|
| Case 1 | 0 | 11.02 | 0.00 |
| Case 2 | 138Ω + 7.6H | 3.33 | 69.78 |
| Case 3 | 172Ω + 5.08H | 2.73 | 75.26 |
| Case 4 | 229Ω + 3.8H | 2.32 | 78.92 |
| Case 5 | 343Ω + 2.53H | 1.57 | 85.79 |
| Case 6 | 686Ω + 169H | 0.92 | 91.66 |

### 4.4.2 Balanced Inductive Load

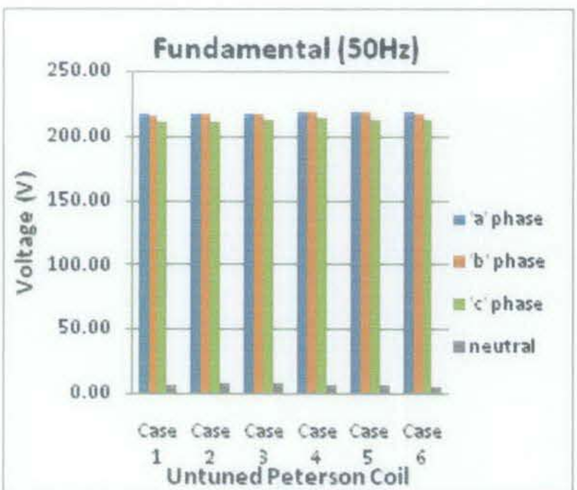



**Figure 88: Fundamental voltage of balanced inductive load with untuned Peterson coil**

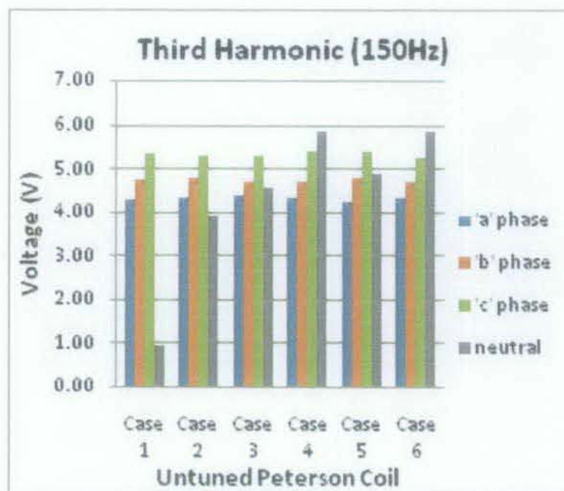



**Figure 89: Third harmonic voltage of balanced inductive load with untuned Peterson coil**

Table 22 show description of Case 1,2,3,4,5 and 6:

**Table 22 – Description of Untuned Peterson Coil for balanced inductive load**

| Case | Untuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H |
| Case 3 | 172Ω + 5.08H |
| Case 4 | 229Ω + 3.8H |
| Case 5 | 343Ω + 2.53H |
| Case 6 | 686Ω + 169H |

For fundamental frequency in figure 88, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 89, all phases of voltages has different magnitude. The third harmonic voltage has positive sequence of phase angle. An example of phase angle data for fundamental and third harmonic voltage with Untuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 90 and figure 91.


**Figure 90: Fundamental voltage phase angle diagram of balanced inductive load with untuned Peterson coil**


**Figure 91: Third harmonic voltage phase angle diagram of balanced inductive load with untuned Peterson coil**

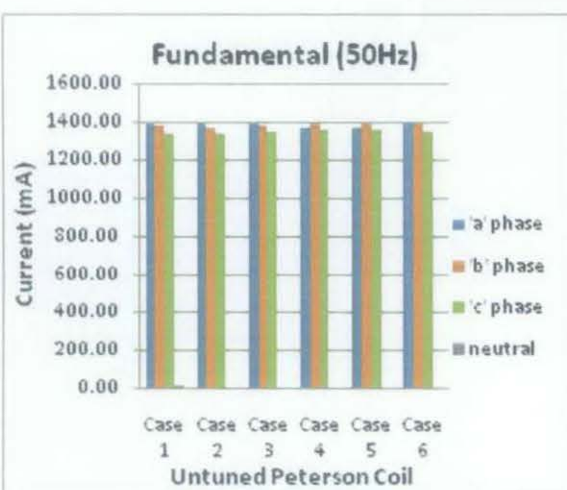



**Figure 92: Fundamental current of balanced inductive load with untuned Peterson coil**

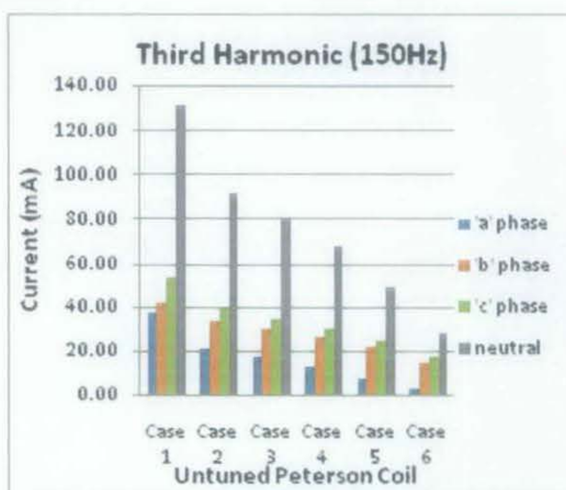



**Figure 93: Third harmonic current of balanced inductive load with untuned Peterson coil**

Table 23 show description of Case 1,2,3,4,5 and 6:

**Table 23 – Description of Untuned Peterson Coil for inductive load**

| Case | Untuned Peterson Coil |
|---|---|
| Case 1 | 0 |
| Case 2 | 138Ω + 7.6H |
| Case 3 | 172Ω + 5.08H |
| Case 4 | 229Ω + 3.8H |
| Case 5 | 343Ω + 2.53H |
| Case 6 | 686Ω + 169H |

For fundamental frequency in figure 92, magnitude of all phases of current is approximately same while for all third harmonic current phases in figure 93, the magnitude are different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the Untuned Peterson Coil resistance and reactance is increasing. The highest neutral third harmonic current is measured when there is no Tuned Peterson Coil being connected. The magnitude of third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Untuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 94 and figure 95.

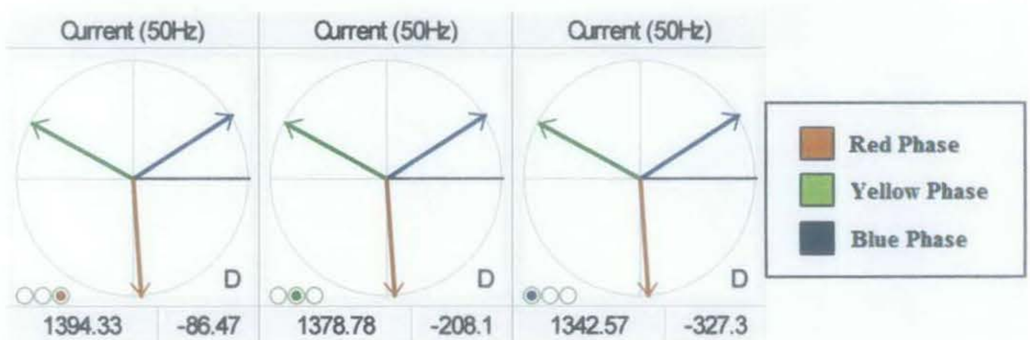



**Figure 94: Fundamental current phase angle diagram of balanced inductive load with untuned Peterson coil**

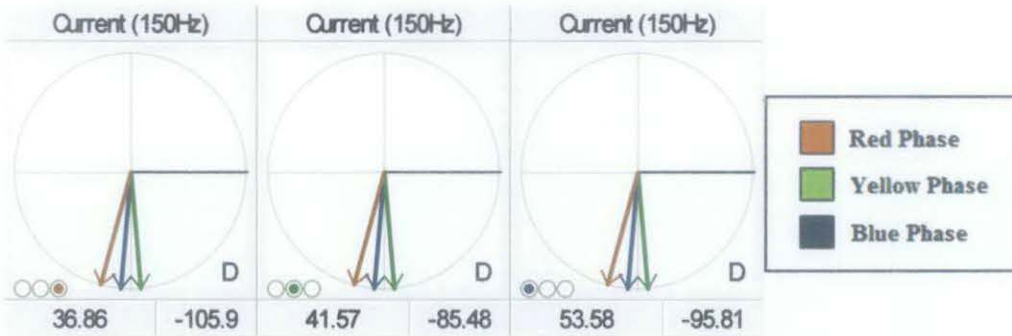



**Figure 95: Third harmonic current phase angle diagram of balanced inductive load with untuned Peterson coil**

Table 24 shows the percentage of reduction between each Untuned Peterson Coil increment.

**Table 24 - Percentage of reduction for balanced inductive load vs. Untuned Peterson Coil**

| Case | Untuned Peterson Coil | Neutral Current (mA) | Percentage of Reduction (%) |
|---|---|---|---|
| Case 1 | 0 | 131.71 | 0.00 |
| Case 2 | 138Ω + 7.6H | 91.90 | 30.22 |
| Case 3 | 172Ω + 5.08H | 81.29 | 38.28 |
| Case 4 | 229Ω + 3.8H | 67.75 | 48.56 |
| Case 5 | 343Ω + 2.53H | 49.22 | 62.63 |
| Case 6 | 686Ω + 169H | 27.92 | 78.80 |

### 4.4.3 Balanced Resistive & Inductive Load


**Figure 96: Fundamental voltage of balanced resistive & inductive load with untuned Peterson coil**

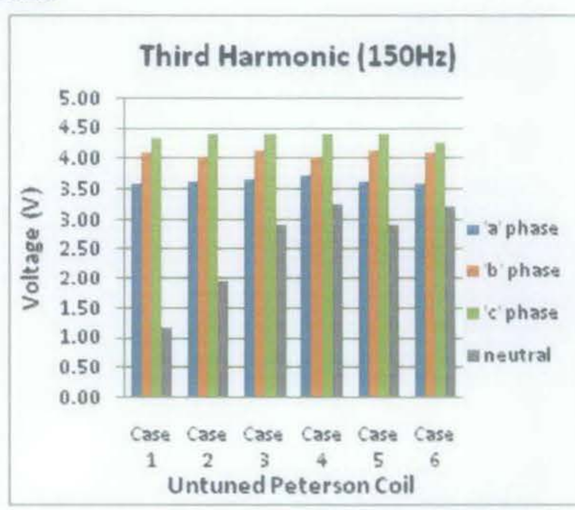



**Figure 97: Third harmonic voltage of balanced resistive & inductive load with untuned Peterson coil**

Table 25 show the description of case 1,2,3,4,5 and 6:

**Table 25 - Description of Untuned Peterson Coil for balanced resistive load**

| Case | Untuned Peterson Coil |
|---|---|
| Case 1 | $\infty$ |
| Case 2 | $138\Omega + 7.6H$ |
| Case 3 | $172\Omega + 5.08H$ |
| Case 4 | $229\Omega + 3.8H$ |
| Case 5 | $343\Omega + 2.53H$ |
| Case 6 | $686\Omega + 169H$ |

For fundamental frequency in figure 96, magnitude of all phases of voltages almost same while for third harmonic frequency in figure 97, all phases of voltages has different magnitude. As Untuned Peterson Coil resistance and reactance increase, magnitude of fundamental and third harmonic voltage remains same. The third harmonic voltage has positive sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with Untuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 98 and figure 99.

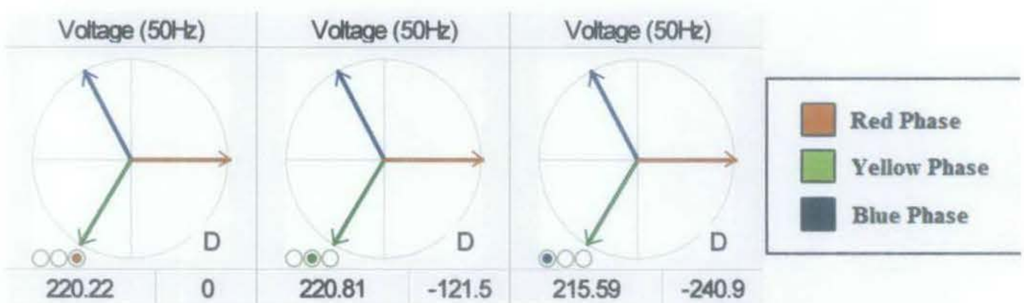



**Figure 98: Fundamental voltage phase angle diagram of balanced resistive & inductive load with untuned Peterson coil**

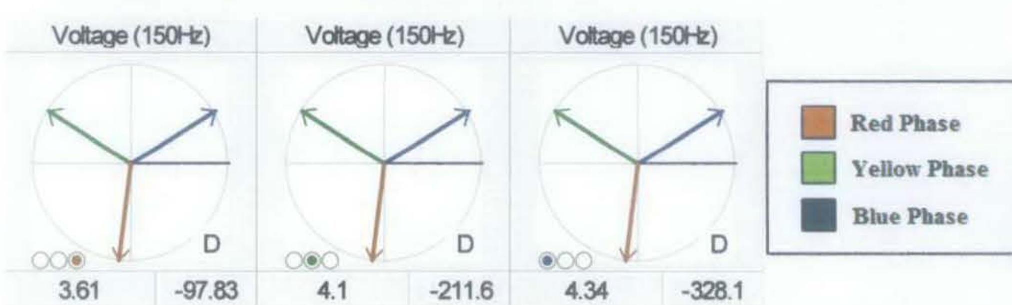



**Figure 99: Third harmonic voltage phase angle diagram of balanced resistive & inductive load with untuned Peterson coil**


**Figure 100: Fundamental current of balanced resistive & inductive load with untuned Peterson coil**

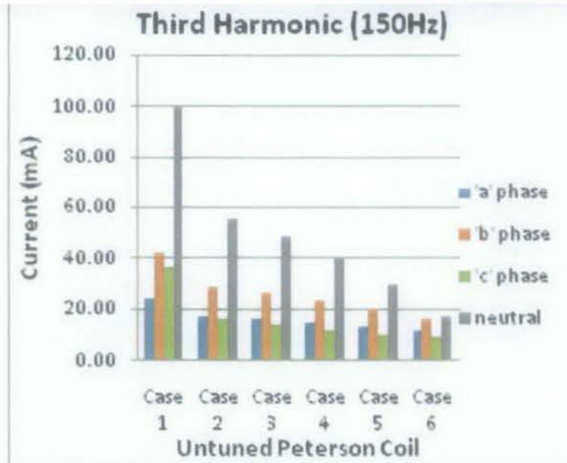



**Figure 101: Third harmonic current of balanced resistive & inductive load with untuned Peterson coil**

For fundamental frequency in figure 100, magnitude of all phases of current is approximately same while for all third harmonic current phases in figure 101, the magnitude are different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the Untuned Peterson Coil resistance and reactance is increasing. The highest neutral third harmonic current is measured when there is no Tuned Peterson Coil being connected. The magnitude of third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with Untuned Peterson Coil of case 1 are used to plot phase angle diagram as in figure 102 and figure 103.

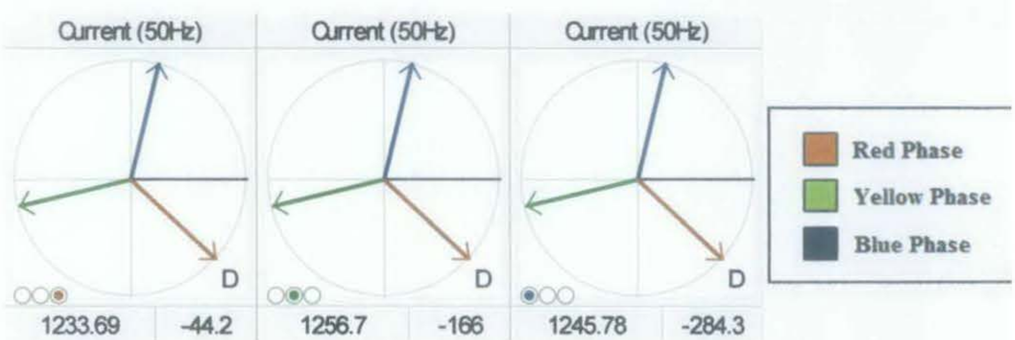



**Figure 102: Fundamental current phase angle diagram of balanced resistive & inductive load with untuned Peterson coil**

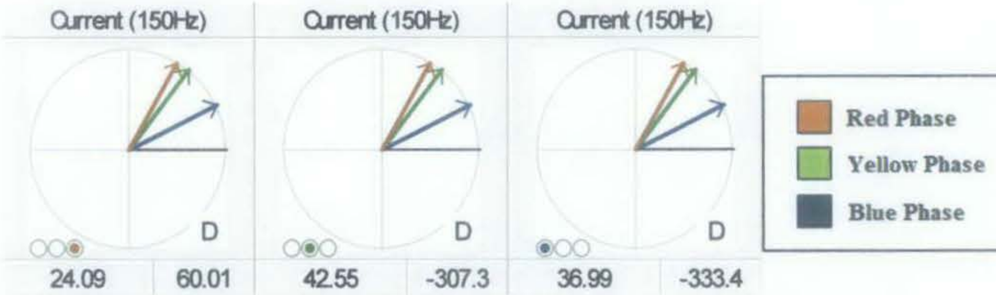



**Figure 103: Third harmonic current phase angle diagram of balanced resistive & inductive load with untuned Peterson coil**

Table 26 shows the percentage of reduction between each Peterson without capacitor coil increment.

**Table 26 - Percentage of reduction for balanced resistive & inductive load vs. Untuned Peterson Coil**

| Case | Untuned Peterson Coil | Neutral Current (mA) | Percentage of Reduction (%) |
|---|---|---|---|
| Case 1 | 0 | 100.33 | 0.00 |
| Case 2 | 138Ω + 7.6H | 56.31 | 43.87 |
| Case 3 | 172Ω + 5.08H | 49.16 | 51.01 |
| Case 4 | 229Ω + 3.8H | 40.42 | 59.71 |
| Case 5 | 343Ω + 2.53H | 29.87 | 70.23 |
| Case 6 | 686Ω + 169H | 17.34 | 82.72 |

## 4.5 Delta Configuration

### 4.5.1 Balance Resistive load

#### 4.5.1.1 Delta-Delta Configuration

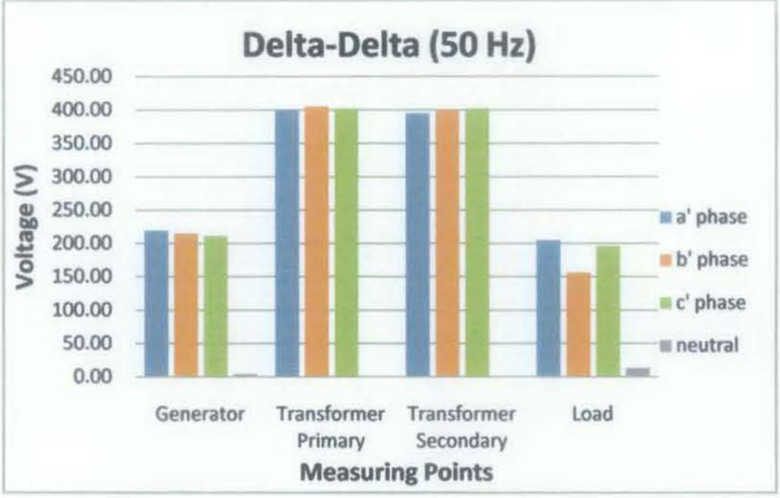



**Figure 104 : Fundamental voltage of balanced resistive load for delta-delta configuration**

For fundamental delta-delta transformer configuration in figure 104, magnitude of all phase voltage is almost same except at load side. Magnitude of voltage for secondary winding is almost same with primary winding side. There is no neutral phase voltage at winding primary and secondary side.

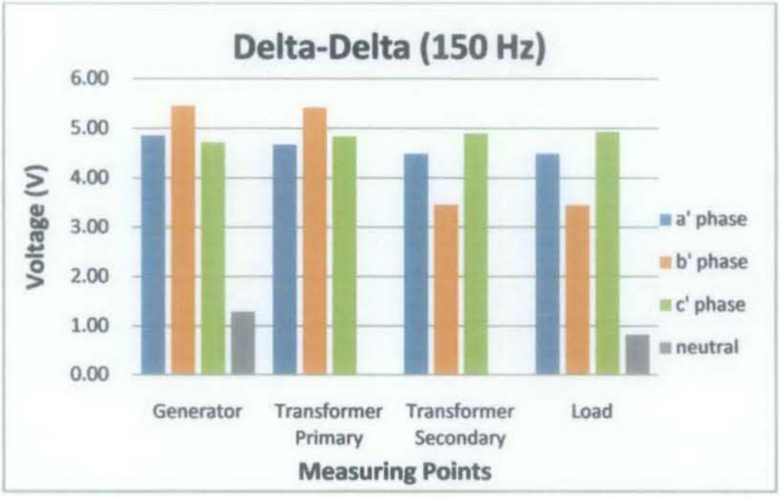



**Figure 105 : Third harmonic voltage of balanced resistive load for delta-delta configuration**

For third harmonic delta-delta transformer configuration in figure 105, magnitude of all phase voltage is different. Magnitude of phase 'a' and 'b' voltage for secondary winding is decreasing compare to primary winding side while phase 'c' is same. There is no neutral phase voltage at winding primary and secondary side.

For third harmonic secondary winding, the voltage has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 106 and figure 107.

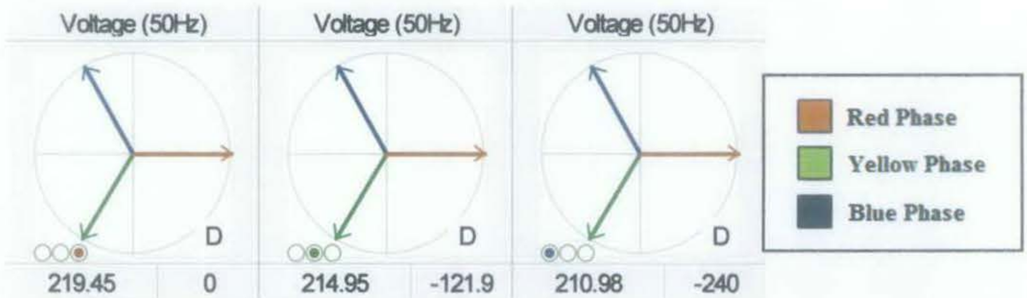



**Figure 106 : Fundamental voltage phase angle diagram of balanced resistive load for delta-delta configuration**

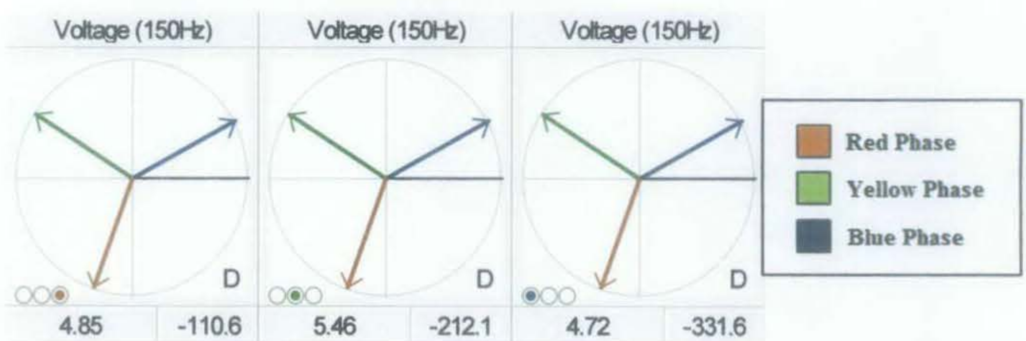



**Figure 107 : Third harmonic voltage phase angle diagram of balanced resistive load for delta-delta configuration**

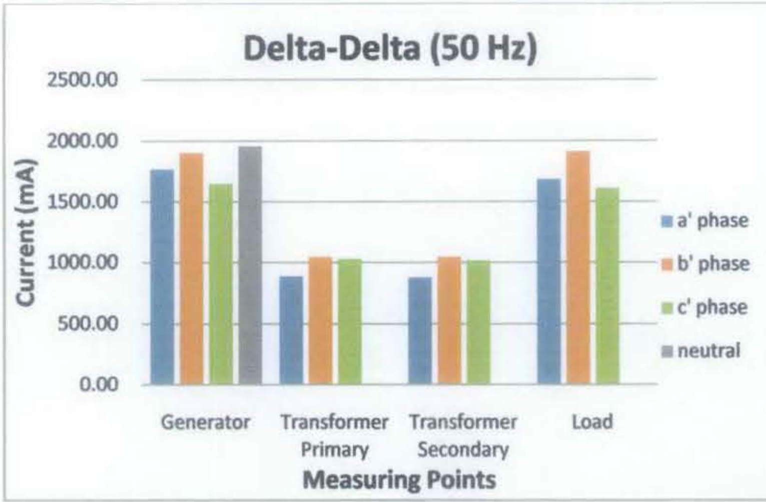



**Figure 108 : Fundamental current of balanced resistive load for delta-delta configuration**

For fundamental delta-delta transformer configuration in figure 108, magnitude of all phase current is different. Magnitude of current for secondary winding is same as primary winding side. There is no neutral phase current at winding primary and secondary side.

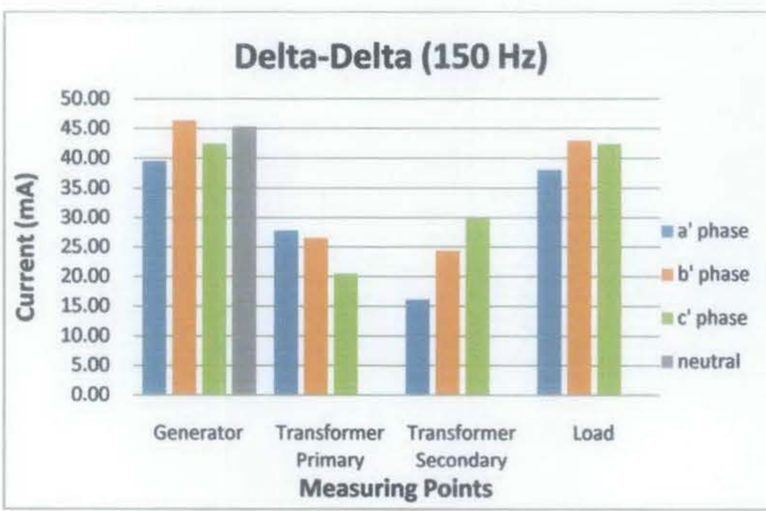



**Figure 109 : Third harmonic current of balanced resistive load for delta-delta configuration**

For third harmonic delta-delta transformer configuration in figure 109, magnitude of all phase current is different. Magnitude of neutral current at load is highly reducing compare to generator side. The secondary winding of third harmonic current has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 110 and figure 111.

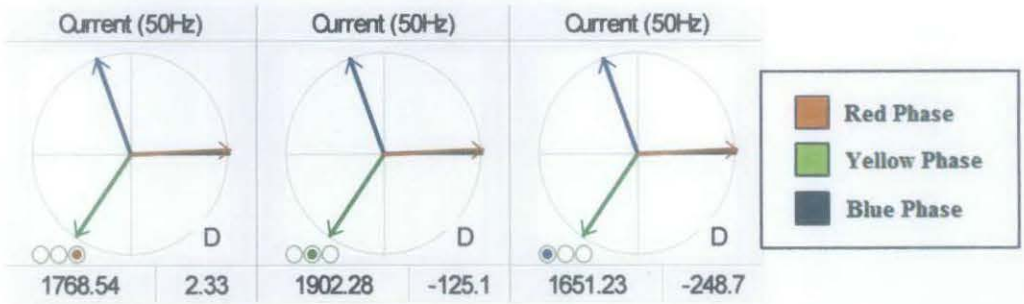



**Figure 110 : Fundamental current phase angle diagram of balanced resistive load for delta-delta configuration**

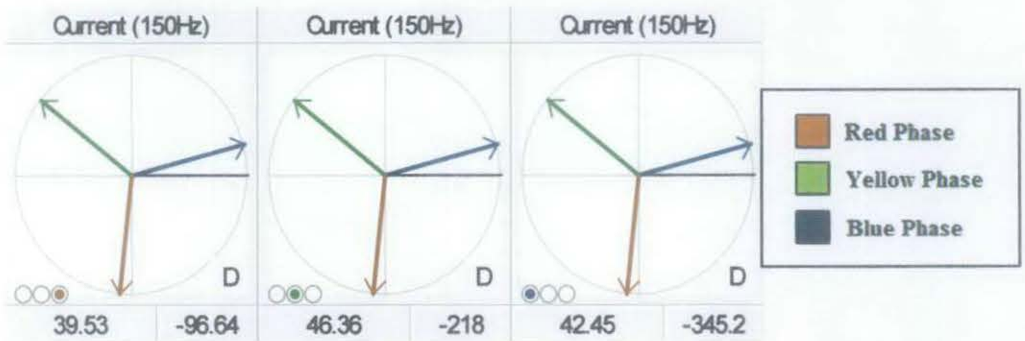



**Figure 111 : Third harmonic current phase angle diagram of balanced resistive load for delta-delta configuration**

From the result, it shows delta-delta configuration does reduce third harmonic current. Third harmonic current is decreasing at load.

#### 4.5.1.2 Delta – Star Configuration

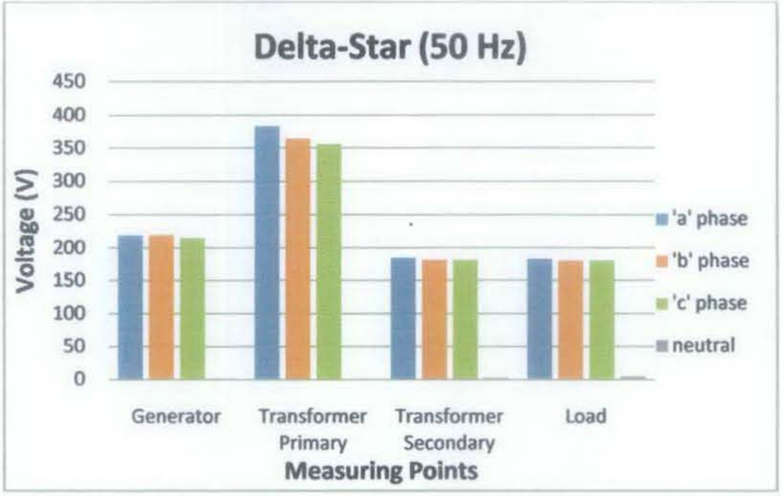



**Figure 112 : Fundamental voltage of balanced resistive load for delta-star configuration**

For fundamental delta-star transformer configuration in figure 112, magnitude of all phase voltage is almost same. Magnitude of voltage for secondary winding is reducing compare to primary winding side. There is small value of neutral phase voltage at all measuring points.

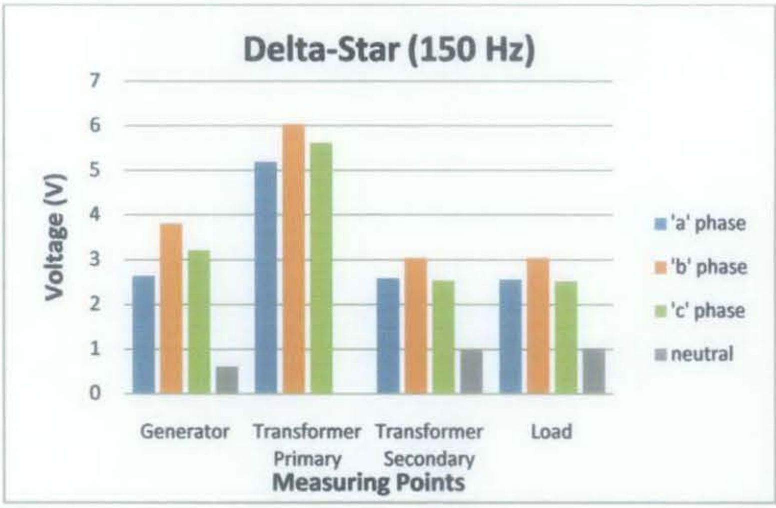



**Figure 113 : Third harmonic voltage of balanced resistive load for delta-star configuration**

For third harmonic delta-star transformer configuration in figure 113, magnitude of all phase voltage is different. Magnitude of all phase voltage for secondary winding is decreasing compare to primary winding side. There is no neutral phase voltage at winding primary side.

For third harmonic secondary winding, the voltage has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 114 and figure 115.


**Figure 114: Fundamental voltage phase angle diagram of balanced resistive load for delta-star configuration**

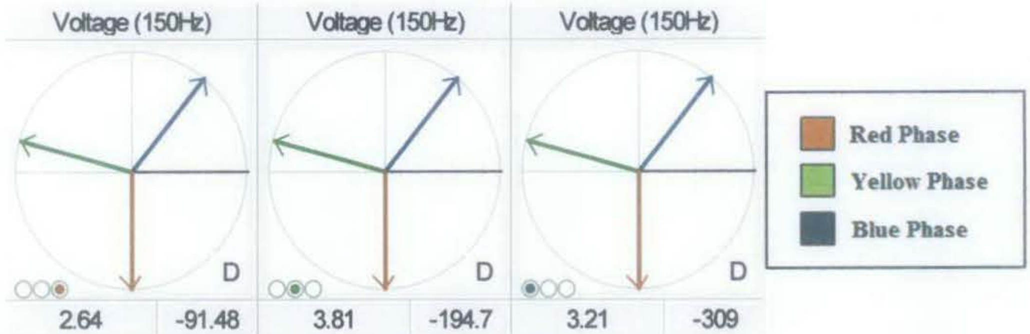



**Figure 115 : Third harmonic voltage phase angle diagram of balanced resistive load for delta-star configuration**

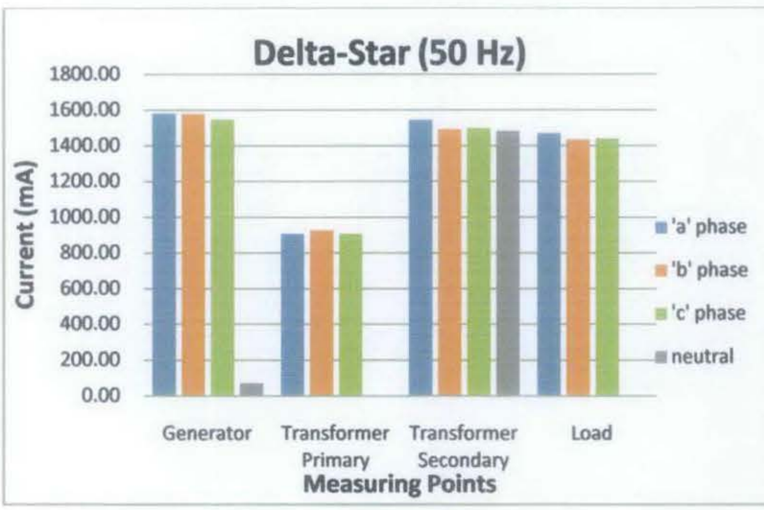



**Figure 116 : Fundamental current of balanced resistive load for delta-star configuration**

For fundamental delta-star transformer configuration in figure 116, magnitude of all phase current is almost same. Magnitude of current for secondary winding is increasing compare to primary winding side. There is high magnitude of neutral phase current for secondary side while no neutral phase current at winding primary side.

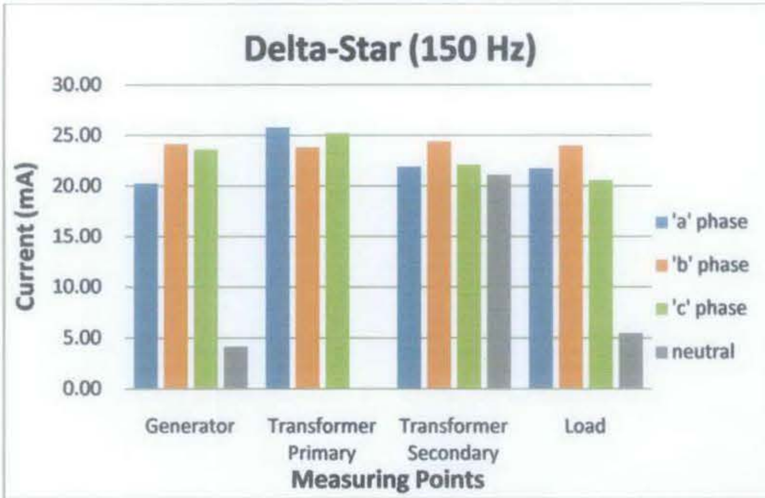



**Figure 117 : Third harmonic current of balanced resistive load for delta-star configuration**

For third harmonic delta-star transformer configuration in figure 117, magnitude of all phase current is different. Magnitude of neutral current for secondary winding is highly increase compare to primary winding side. The secondary winding of third harmonic current has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 118 and figure 119.

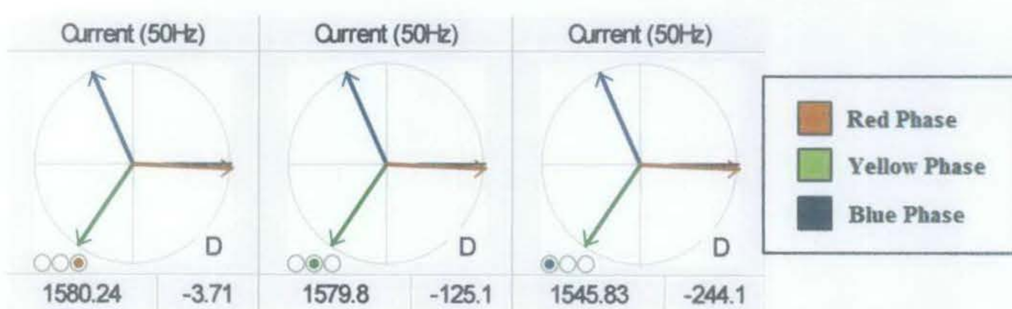



**Figure 118 : Fundamental current phase angle voltage of balanced resistive load for delta-star configuration**

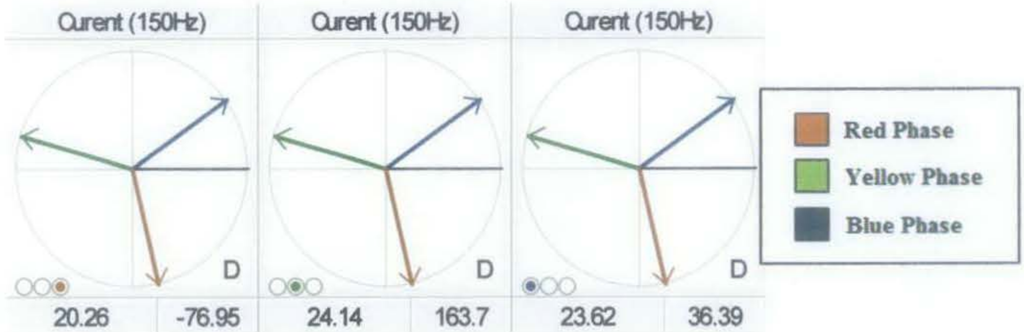



**Figure 119 : Third harmonic current phase angle diagram of balanced resistive load for delta-star configuration**

From the result, it show that delta-star transformer configuration do not block third harmonic current. Third harmonic current is increase in secondary winding.

#### 4.5.1.3 Star - Delta Configuration


**Figure 120 : Fundamental voltage of balanced resistive load for star-delta configuration**

For fundamental star-delta transformer configuration in figure 120, magnitude of all phase voltage is almost same. Magnitude of voltage for all side also almost same. There is no value of neutral phase voltage at secondary winding side.

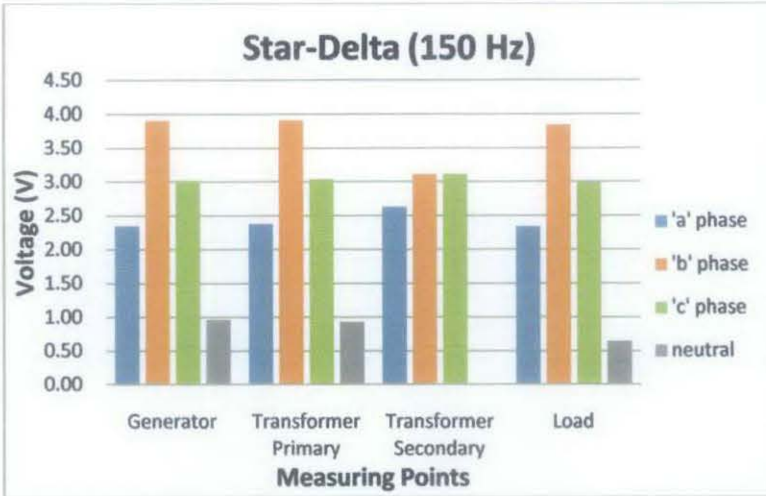



**Figure 121 : Third harmonic voltage of balanced resistive load for star-delta configuration**

For third harmonic star-delta transformer configuration in figure 121, magnitude of all phase voltage is different. Magnitude of phase 'a' voltage for secondary winding is increasing compare to primary winding side while for phase 'b', the voltage is reduce at secondary winding . There is no neutral phase voltage at winding secondary side. For third harmonic secondary winding, the voltage has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 122 and figure 123.

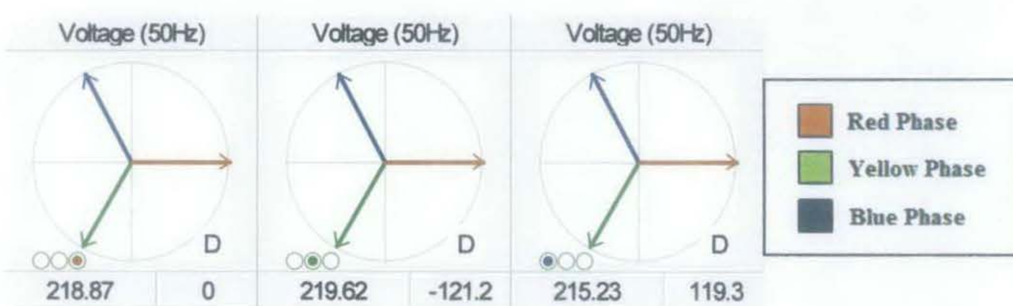



**Figure 122 : Fundamental voltage phase angle diagram of balanced resistive load for star-delta configuration**

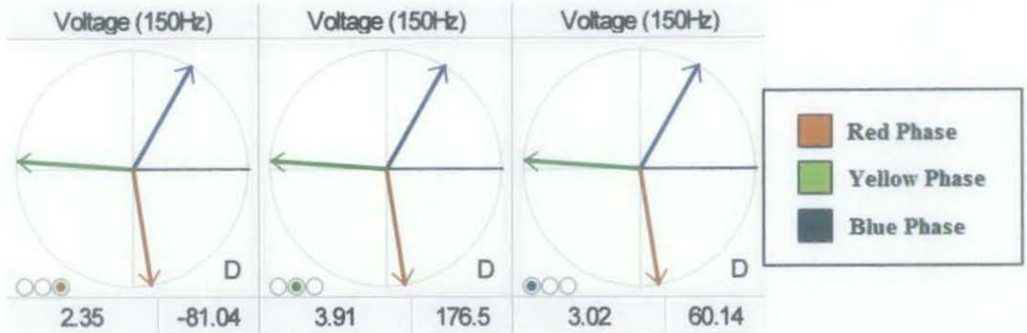



**Figure 123 : Fundamental voltage phase angle diagram of balanced resistive load for star-delta configuration**


**Figure 124 : Fundamental current of balanced resistive load for star-delta configuration**

For fundamental star-delta transformer configuration in figure 124, magnitude of all phase current is almost same except for secondary winding. Magnitude of current phase for secondary winding is decreasing compare to primary winding side. There is high magnitude of neutral phase current at generator side while small neutral phase current at other measurement points.

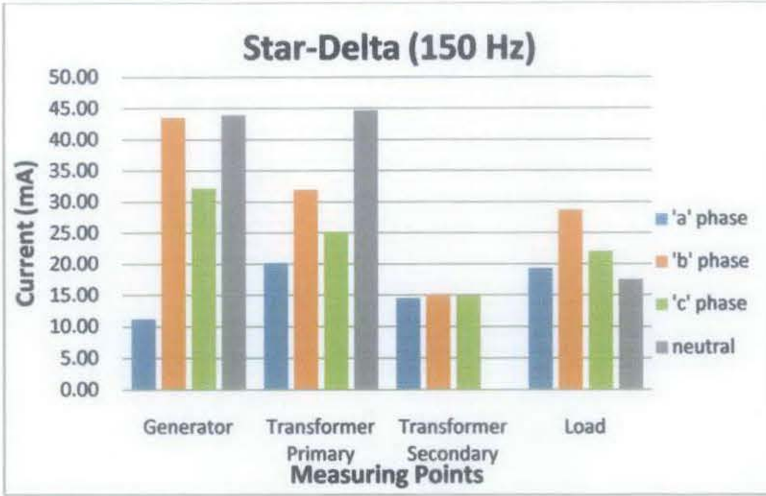



**Figure 125 : Third harmonic current of balanced resistive load for star-delta configuration**

For third harmonic star-delta transformer configuration in figure 125, magnitude of all phase current is different. Magnitude of neutral current for secondary winding is highly decrease compare to primary winding side. The secondary winding of third harmonic current has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 126 and figure 127.

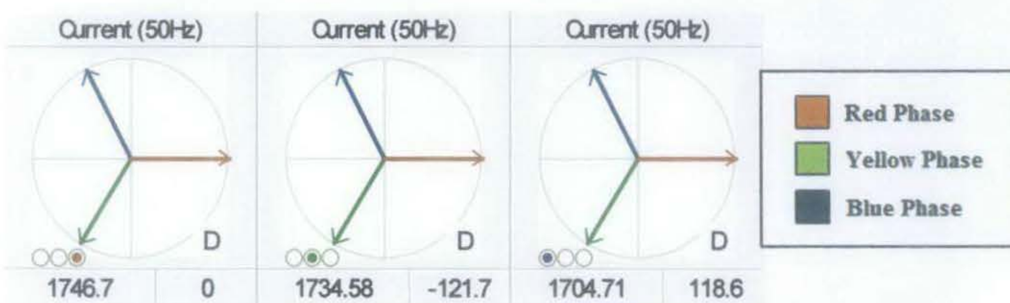



**Figure 126 : Fundamental current phase angle diagram of balanced resistive load for star-delta configuration**

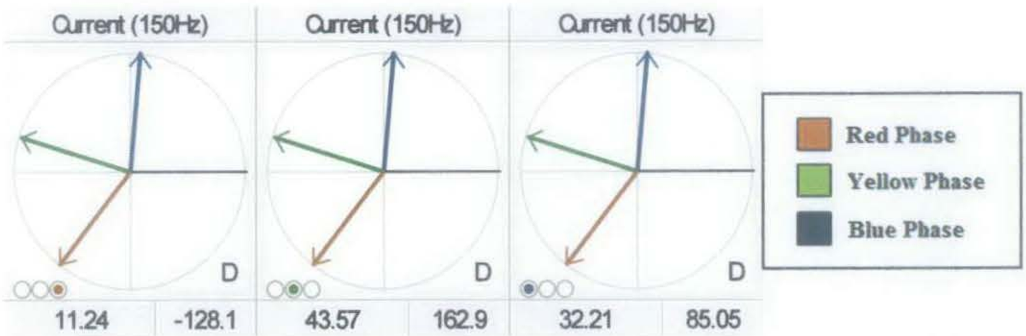



**Figure 127 : Third harmonic current phase angle diagram of balanced resistive load for star-delta configuration**

From the result, it shows that star-delta transformer configuration does reduce third harmonic current. There is third harmonic current at load side.

### 4.5.2 Balanced Inductive Load

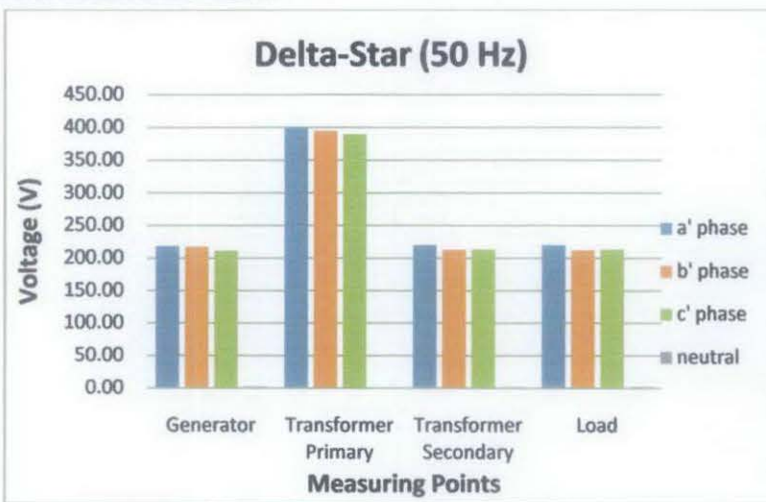



**Figure 128: Fundamental voltage of balanced inductive load for delta-star configuration**

For fundamental delta-star transformer configuration in figure 128, magnitude of all phase voltage is almost same. Magnitude of voltage for secondary winding is reducing compare to primary winding side. There is small magnitude of neutral phase voltage for secondary side while no neutral phase voltage at winding primary side.

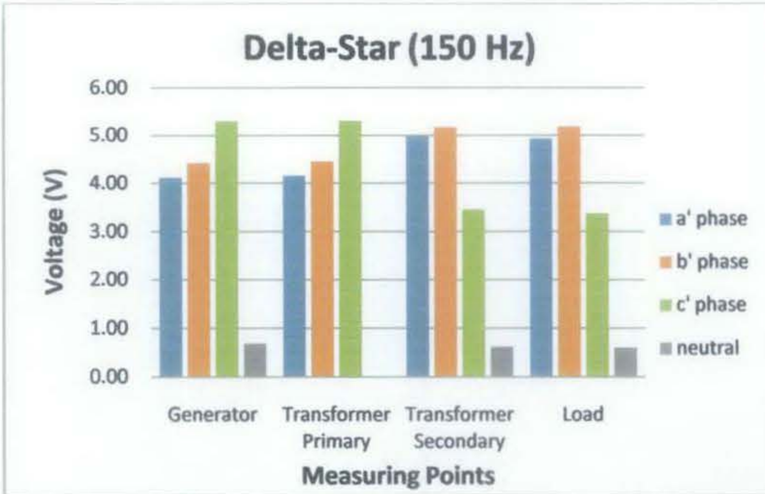



**Figure 129: Third harmonic voltage of balanced inductive load for delta-star configuration**

For third harmonic delta-star transformer configuration in figure 129, magnitude of all phase voltage is different. Magnitude of phase 'a' and 'b' voltage for secondary winding is increasing compare to primary winding side while phase 'c' is reducing. There is small magnitude of neutral phase voltage for secondary side while no neutral phase voltage at winding primary side.

For third harmonic secondary winding, the voltage has positive sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 130 and figure 131.


**Figure 130: Fundamental voltage phase angle diagram of balanced inductive load for delta-star configuration**

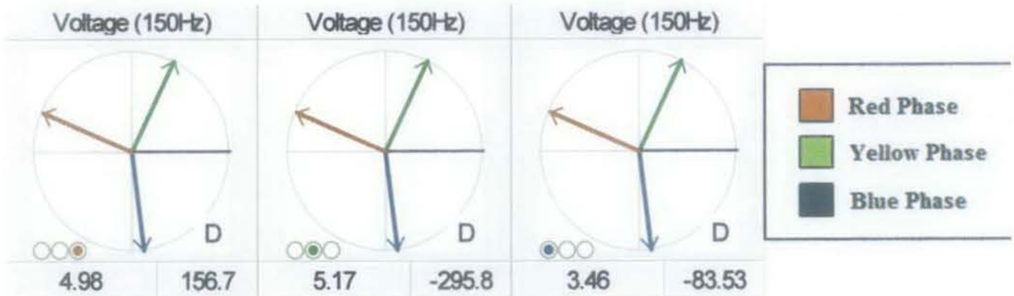



**Figure 131: Third harmonic voltage phase angle diagram of balanced inductive load for delta-star configuration**

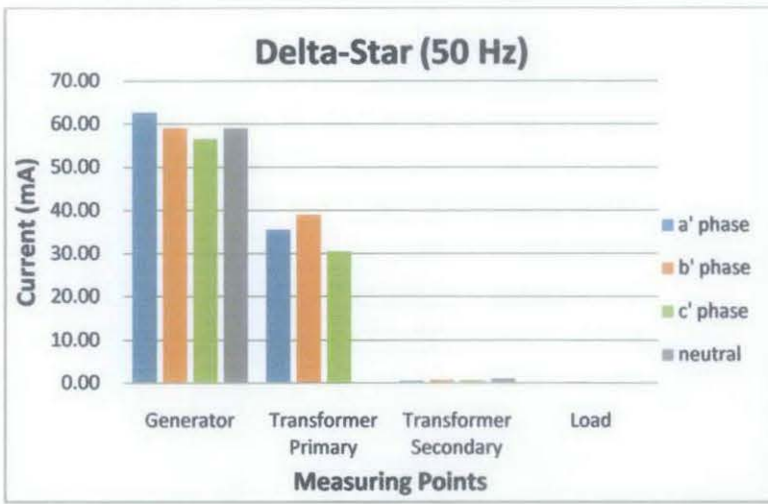



**Figure 132: Fundamental current of balanced inductive load for delta-star configuration**

For fundamental delta-star transformer configuration in figure 132, magnitude of all phase current is different. Magnitude of current for secondary winding is reducing compare to primary winding side. There is small magnitude of neutral phase voltage for secondary side while no neutral phase current at winding primary side.

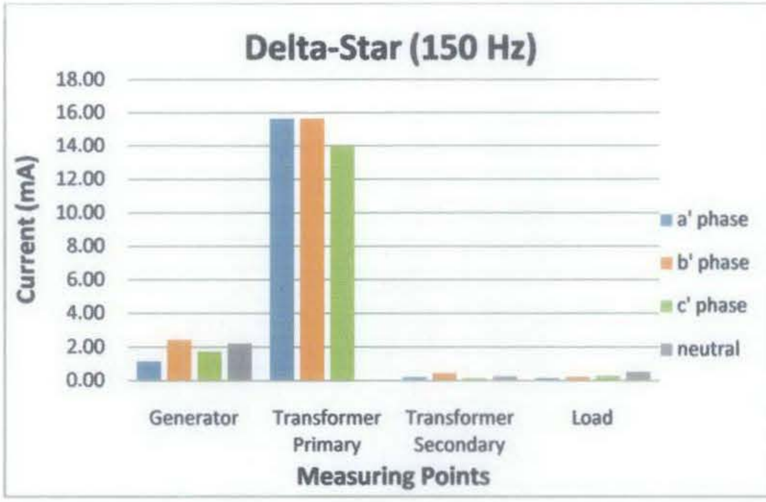



**Figure 133: Third harmonic current of balanced inductive load for delta-star configuration**

For third harmonic delta-star transformer configuration in figure 133, magnitude of all phase current is different. Magnitude of neutral current for secondary winding is highly reducing compare to primary winding side. The secondary winding of third harmonic current has zero sequence of phase angle. Examples of phase angle data for fundamental and third harmonic secondary winding voltage are used to plot phase angle diagram as in figure 134 and figure 135.

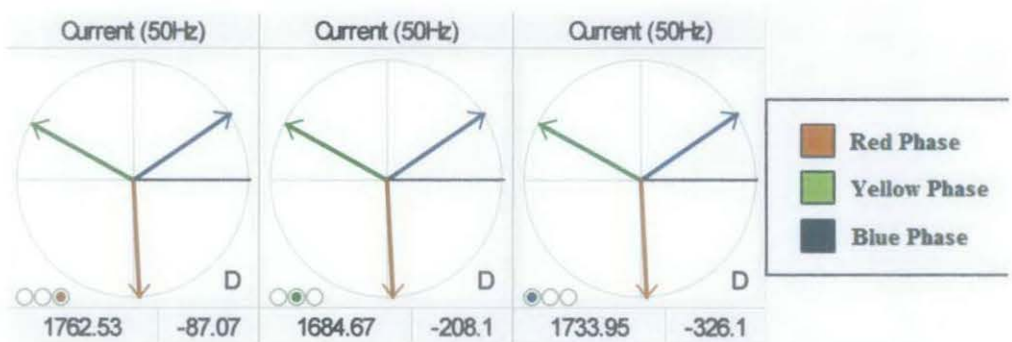



**Figure 134: Fundamental current phase angle diagram of balanced inductive load for delta-star configuration**

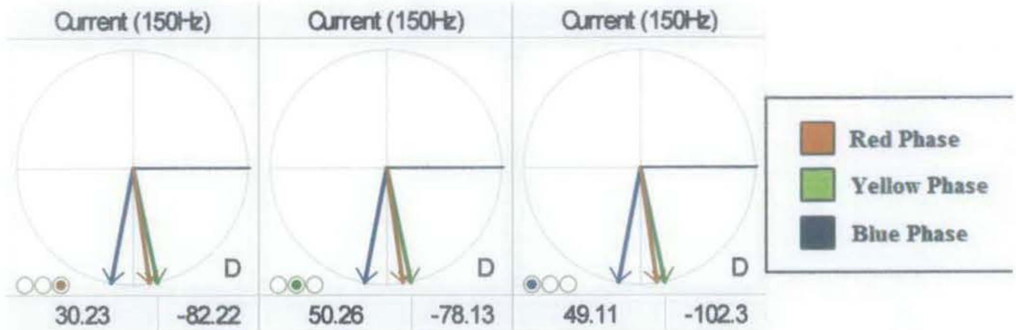



**Figure 135: Third harmonic current phase angle diagram of balanced inductive load for delta-star configuration**

From the result, it show that delta-star transformer configuration do not block third harmonic current. Third harmonic current is increase in secondary winding compare to primary winding.

# PARALLEL BETWEEN GRID AND GENERATOR

## 4.6 Generator NER

### 4.6.1 Balanced Inductive Load


**Figure 136: Fundamental voltage of balanced inductive load with NER at generator side**

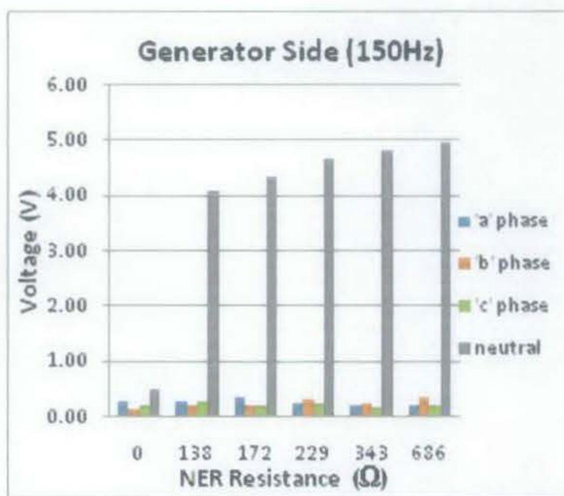



**Figure 137: Third harmonic voltage of balanced inductive load with NER at generator side**

Magnitude of all phases of voltages for fundamental frequency in figure 136 and third harmonic frequency in figure 137 is almost same. As NER resistance increase, magnitude of fundamental & third harmonic voltage stays almost same except for neutral phase voltage. The lowest third harmonic neutral phase voltage is measured when there is no NER connected. The third harmonic voltage has zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with no NER resistance are used to plot phase angle diagram as in figure 138 and figure 139.


**Figure 138: Fundamental voltage phase angle diagram of balanced inductive load with NER at generator side**

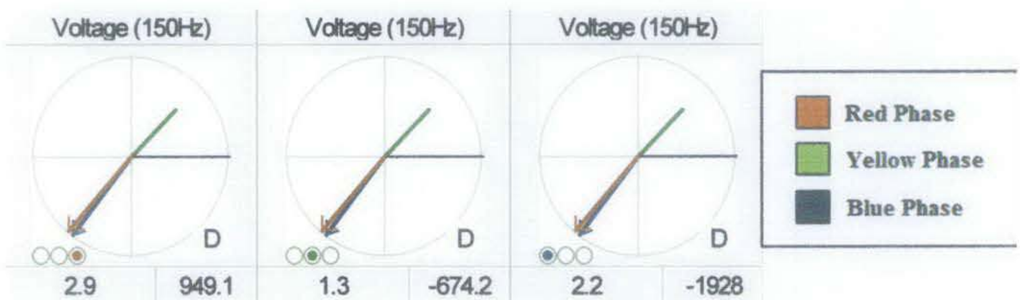



**Figure 139: Third harmonic voltage phase angle diagram of balanced inductive load with NER at generator side**

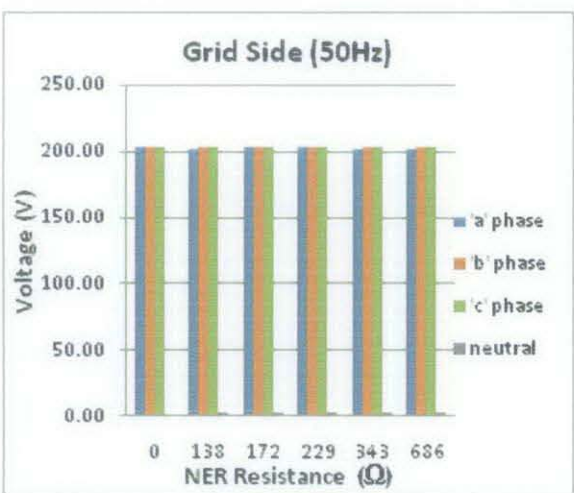



**Figure 140: Fundamental voltage of balanced inductive load with NER at grid side**

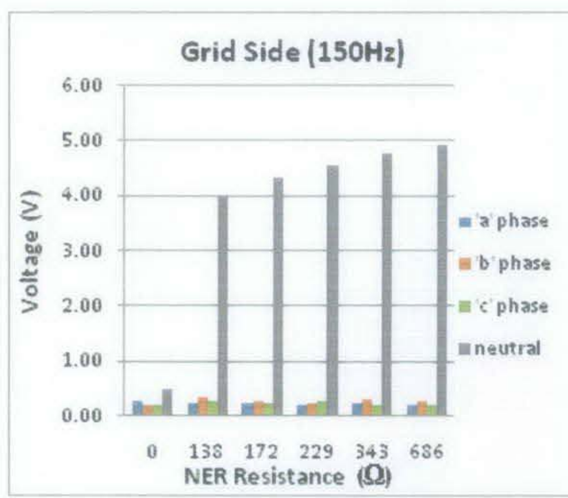



**Figure 141: Third harmonic voltage of balanced inductive load with NER at grid side**

Magnitude of all phases of voltages for fundamental frequency in figure 140 and third harmonic frequency in figure 141 is almost same. As NER resistance increase, magnitude of fundamental & third harmonic voltage stays almost same except for third harmonic neutral phase voltage. The lowest third harmonic neutral phase voltage is measured when there is no NER connected. The fundamental voltage has positive sequence of phase angle while third harmonic voltage has zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with no NER resistance are used to plot phase angle diagram as in figure 142 and figure 143.

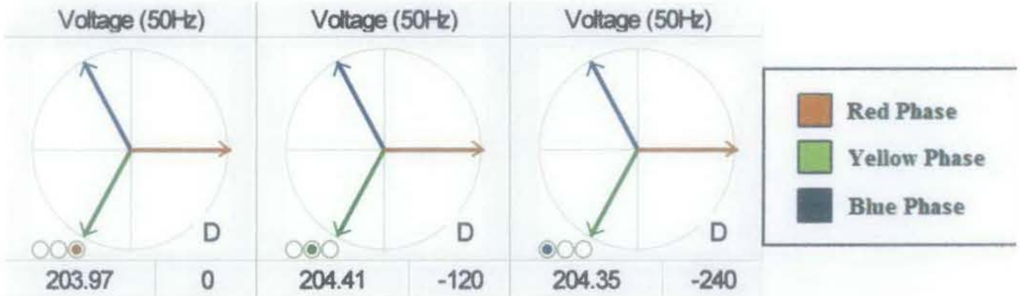



**Figure 142: Fundamental voltage of phase angle diagram of balanced inductive load with NER at grid side**

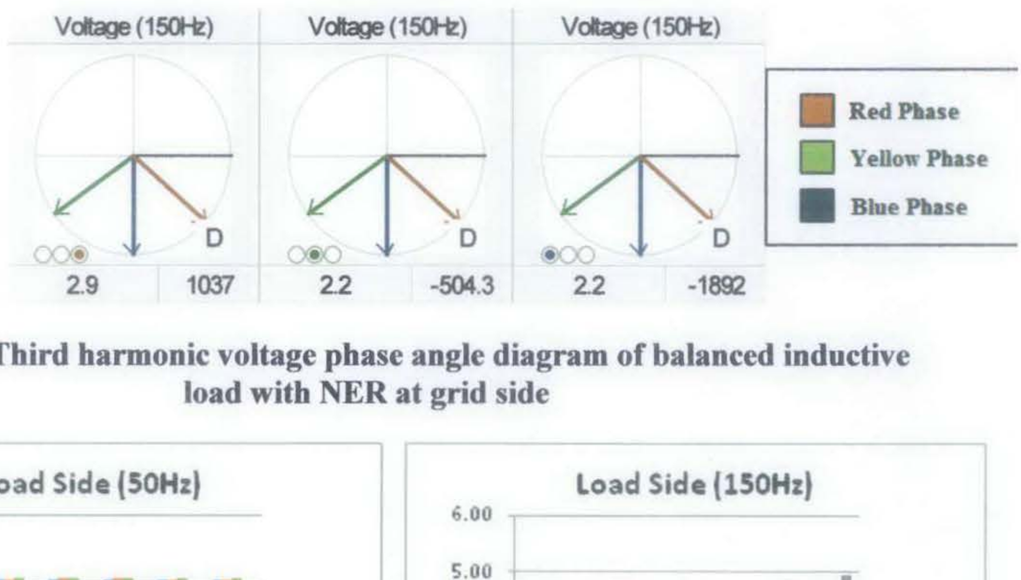



**Figure 143: Third harmonic voltage phase angle diagram of balanced inductive load with NER at grid side**

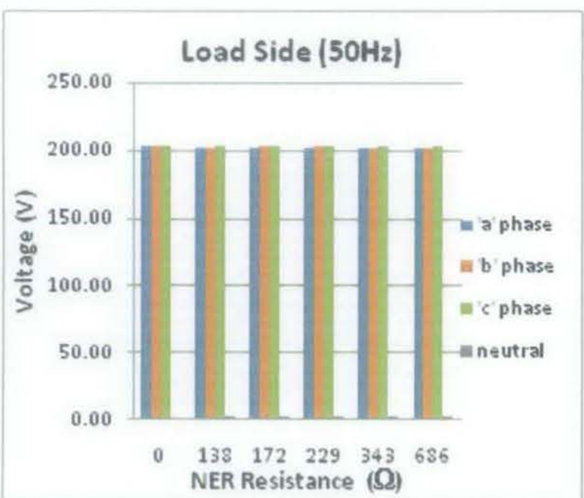



**Figure 144: Fundamental voltage of balanced inductive load with NER at load side**

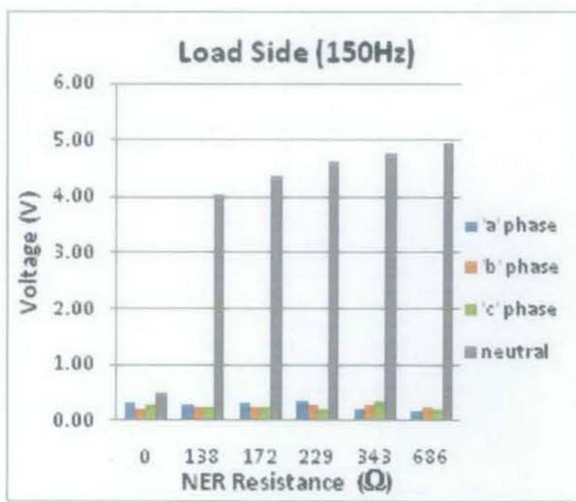



**Figure 145: Third harmonic voltage of balanced inductive load with NER at load side**

Magnitude of all phases of voltages for fundamental frequency as in figure 144 and third harmonic frequency in figure 145 is almost same. As NER resistance increase, magnitude of fundamental & third harmonic voltage stays almost same except for third harmonic neutral phase voltage. The lowest third harmonic neutral phase voltage is measured when there is no NER connected. The harmonic voltage has zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic voltage with no NER resistance are used to plot phase angle diagram as in figure 146 and figure 147.

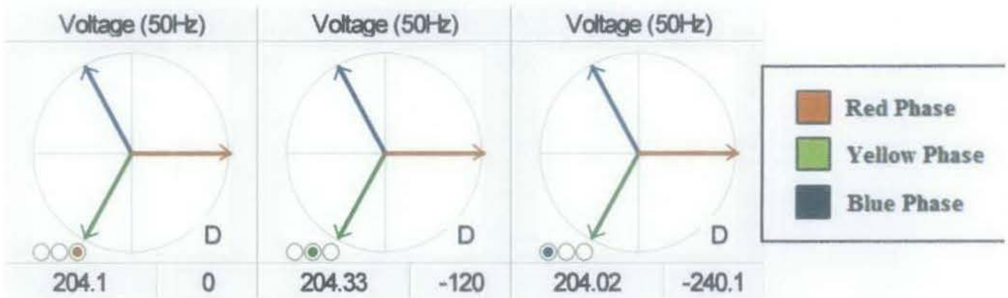



**Figure 146: Fundamental voltage phase angle diagram of balanced inductive load with NER at load side**

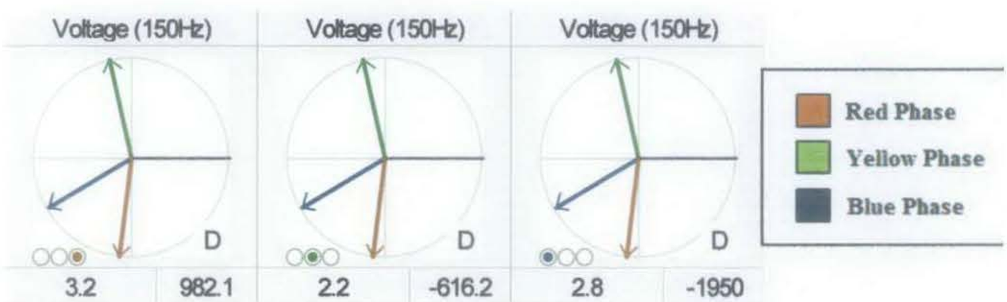



**Figure 147: Third harmonic voltage phase angle diagram of balanced inductive load with NER at load side**

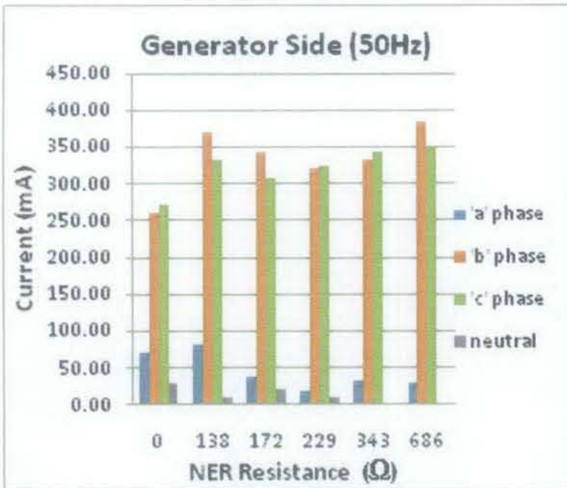



**Figure 148: Fundamental current of balanced inductive load with NER at generator side**

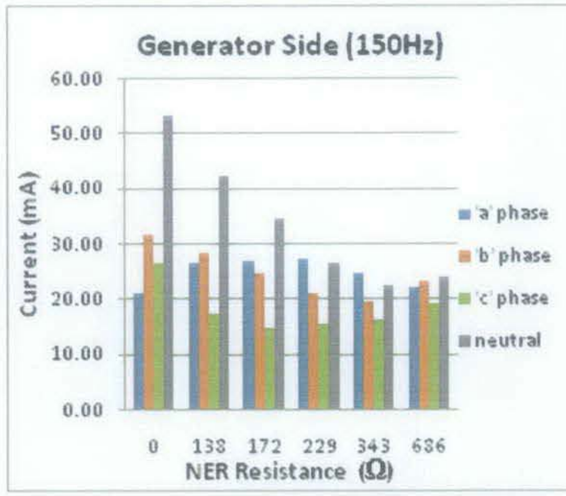



**Figure 149: Third harmonic current of balanced inductive load with NER at generator side**

Magnitude of all phases of current for fundamental frequency in figure 148 and third harmonic frequency in figure 149 is different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the NER resistance is increasing. The highest neutral third harmonic current is measured when there is no NER being connected. The third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with no NER resistance are used to plot phase angle diagram as in figure 150 and figure 151.

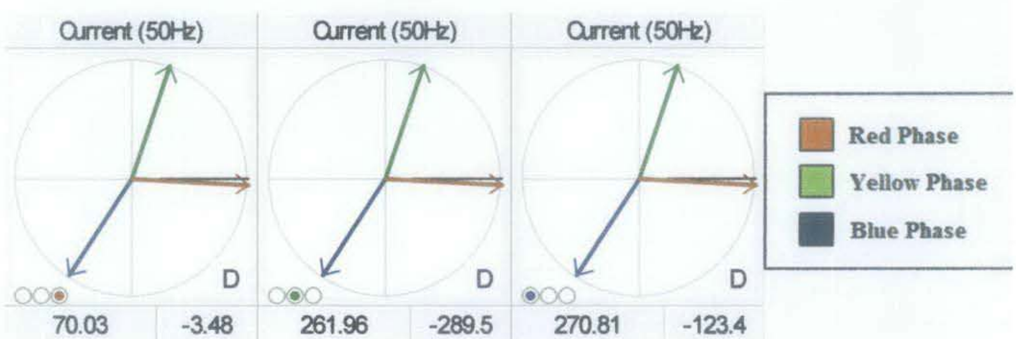



**Figure 150: Fundamental current phase angle diagram of balanced inductive load with NER at generator side**

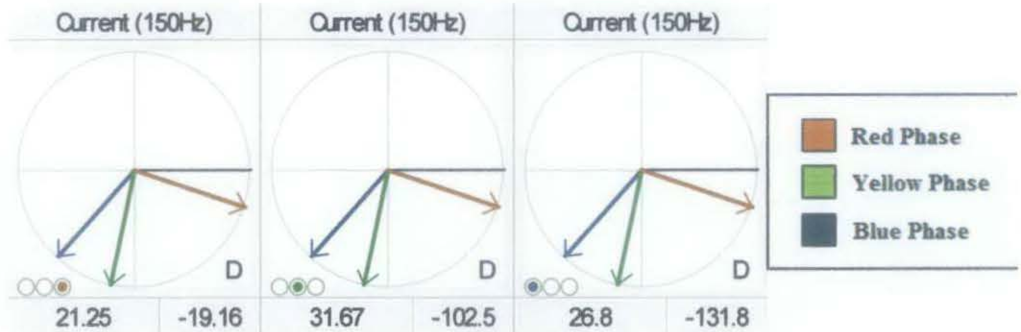



**Figure 151: Third harmonic current phase angle diagram of balanced inductive load with NER at generator side**

Table 27 shows the percentage of reduction between each NER increment.

**Table 27 - Percentage of reduction for balanced inductive load vs. NER at generator side**

| NER (Ω) | Neutral Current (mA) | Percentage of Reduction (%) |
|---|---|---|
| 0 | 53.32 | 0.00 |
| 138 | 42.56 | 20.18 |
| 172 | 34.92 | 34.50 |
| 229 | 26.86 | 49.62 |
| 343 | 22.55 | 57.71 |
| 686 | 24.15 | 54.71 |

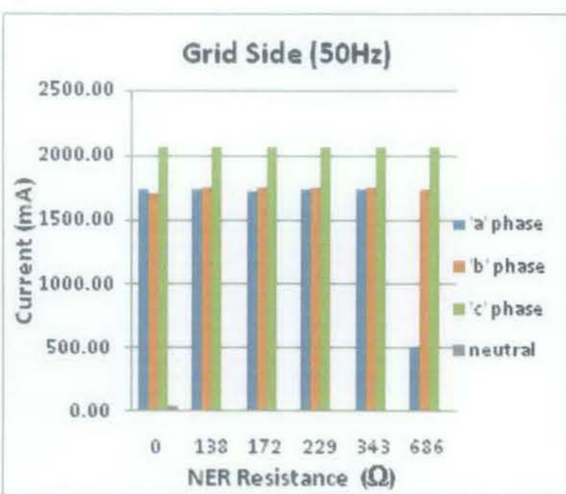



**Figure 152: Fundamental current of balanced inductive load with NER at grid side**

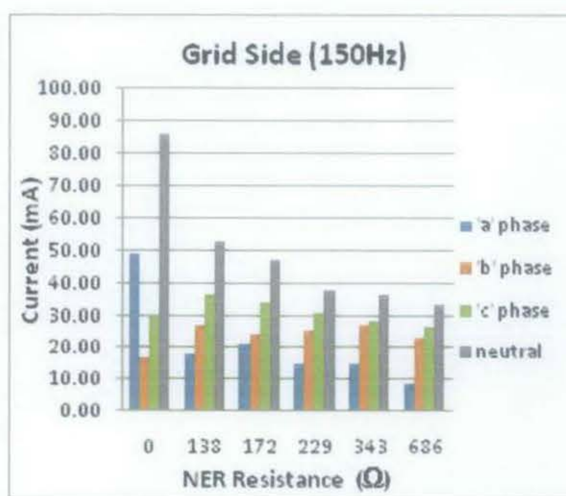



**Figure 153: Third harmonic current of balanced inductive load with NER at grid side**

Magnitude of all phases of current for fundamental frequency in figure 152 and third harmonic frequency in figure 153 is different. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the NER resistance is increasing. The highest neutral third harmonic current is measured when there is no NER being connected. The third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with no NER resistance are used to plot phase angle diagram as in figure 154 and figure 155.

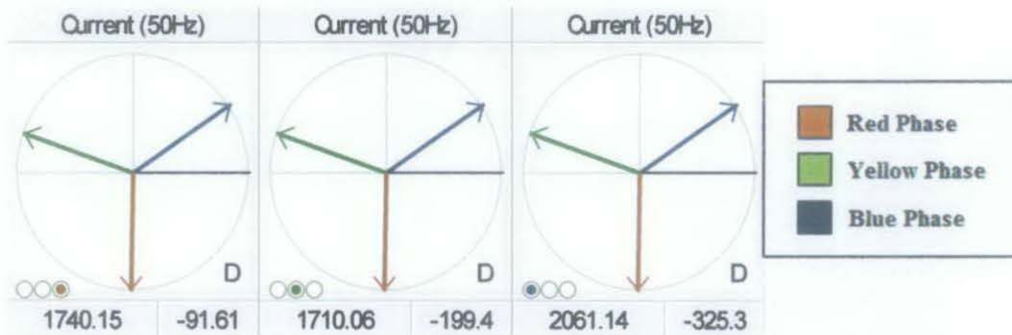



**Figure 154: Fundamental current phase angle diagram of balanced inductive load with NER at grid side**

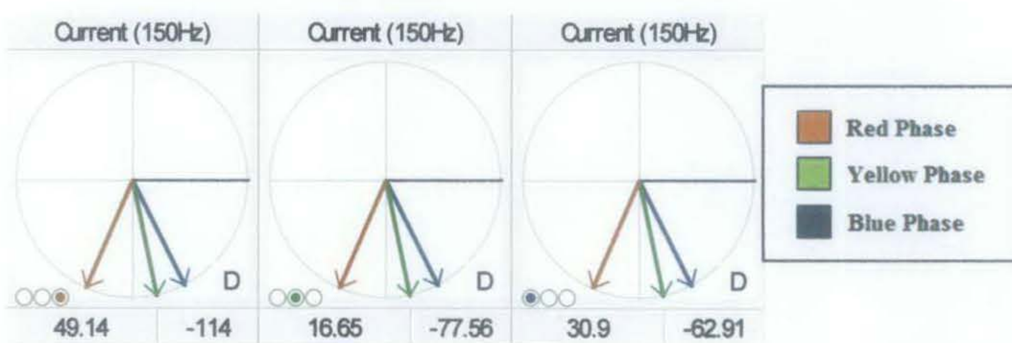



**Figure 155: Third harmonic current phase angle diagram of balanced inductive load with NER at grid side**

Table 28 shows the percentage of reduction between each NER increment.

**Table 28 - Percentage of reduction for balanced inductive load vs. NER at grid side**

| **NER** (Ω) | **Neutral Current** (mA) | **Percentage of Reduction** (%) |
|---|---|---|
| 0 | 86.16 | 0.00 |
| 138 | 53.34 | 38.09 |
| 172 | 47.21 | 45.21 |
| 229 | 38.09 | 55.79 |
| 343 | 36.80 | 57.29 |

| | | |
|---|---|---|
| 686 | 33.58 | 61.03 |


Figure 156: Fundamental current of balanced inductive load with NER at load side

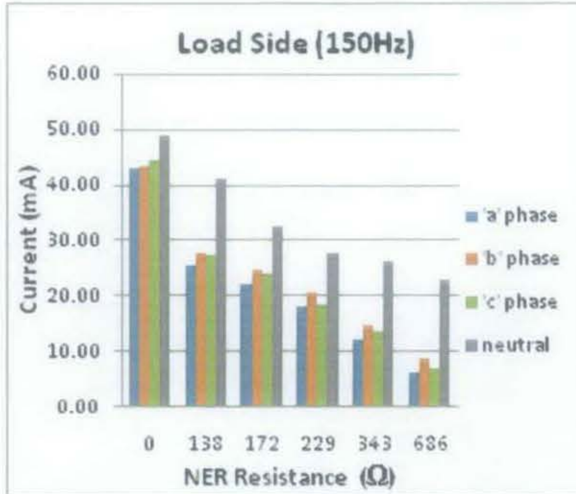



Figure 157: Third harmonic current of balanced inductive load with NER at load side

Magnitude of all phases of current for fundamental frequency in figure 156 and third harmonic frequency in figure 157 is almost same. The value of neutral current for fundamental frequency is quite small. The magnitude of neutral current for third harmonic frequency is decreasing as the NER resistance is increasing. The highest neutral third harmonic current is measured when there is no NER being connected. The third harmonic neutral current is three times the phase current due to zero sequence of phase angle. Example of phase angle data for fundamental and third harmonic current with no NER resistance are used to plot phase angle diagram as in figure 158 and figure 159.

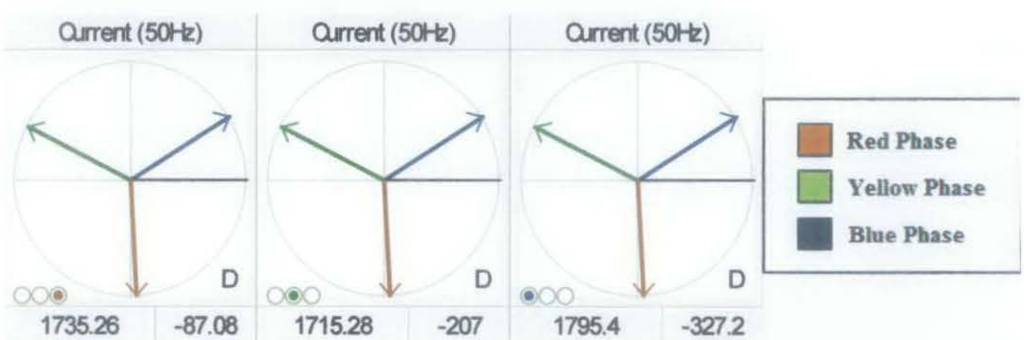



Figure 158: Fundamental current phase angle diagram of balanced inductive load with NER at load side

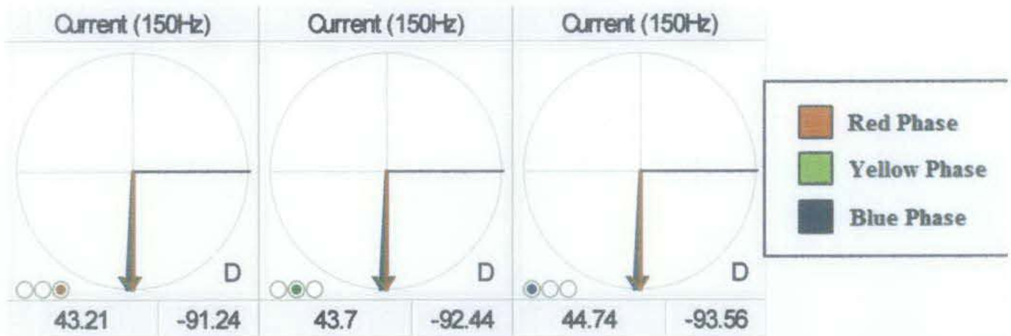



**Figure 159: Third harmonic current phase angle diagram of balanced inductive load with NER at load side**

Table 29 shows the percentage of reduction between each NER increment.

**Table 29 - Percentage of reduction for balanced inductive load vs. NER at load side**

| NER (Ω) | Neutral Current (mA) | Percentage of Reduction (%) |
|---|---|---|
| 0 | 49.30 | 0.00 |
| 138 | 41.39 | 16.06 |
| 172 | 32.83 | 33.40 |
| 229 | 27.83 | 43.55 |
| 343 | 26.35 | 46.55 |
| 686 | 23.18 | 52.99 |

# CHAPTER 5

# SIMULATION RESULT & DISCUSSION

The objective of PSCAD simulation is to model the correct harmonic source in time domain. Only third harmonic voltage and current will be discussed in this chapter.

## SINGLE GENERATOR – SIMULATION MODEL

### 5.1 Variation Load

#### 5.1.1 Balanced Resistive Load

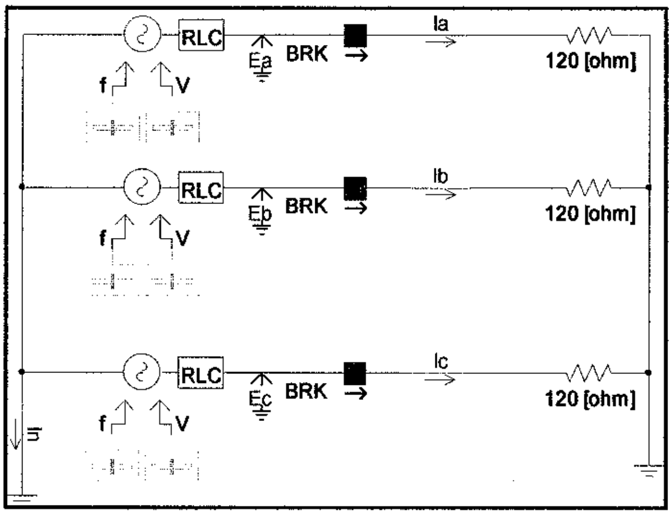



**Figure 160 – Simulation Model for Balanced Resistive Load**

#### 5.1.2 Balanced Inductive Load

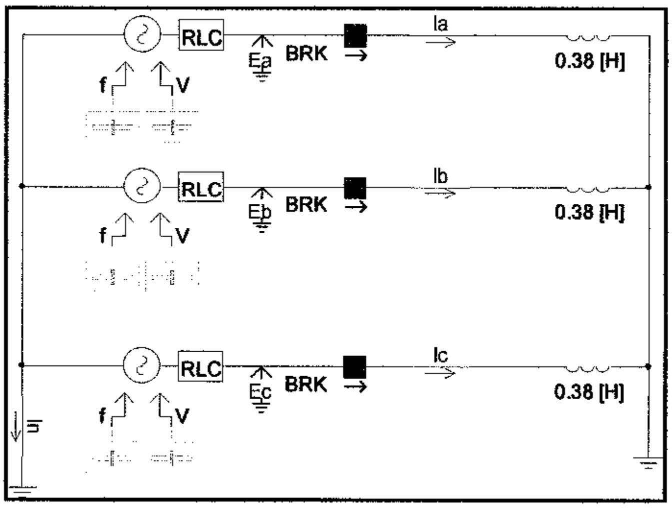



**Figure 161 - Simulation Model for Balanced Inductive Load**

### 5.1.3 Balanced Resistive & Inductive Load

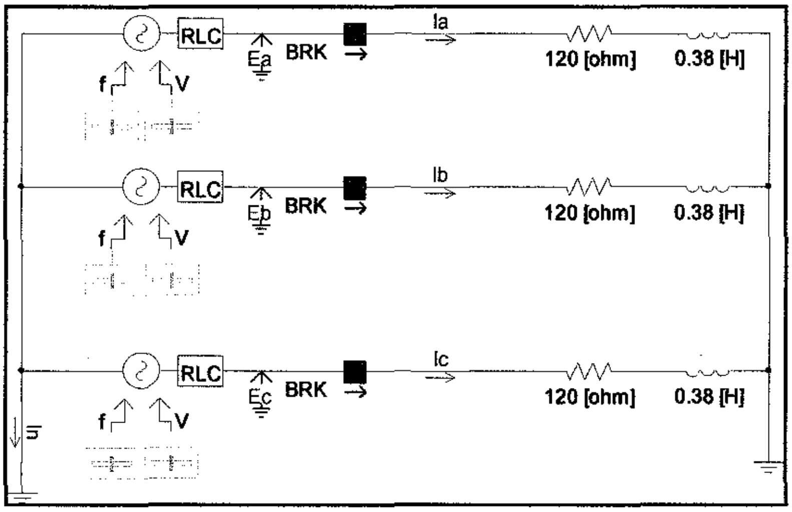



**Figure 162 - Simulation Model of Balanced Resistive & Inductive Load**

## 5.2 Generator NER

### 5.2.1 Balanced Resistive Load

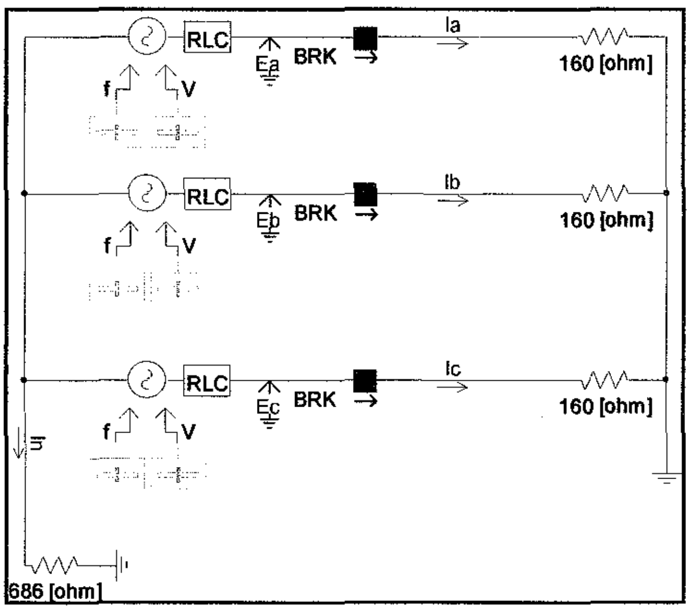



**Figure 163 - Simulation Model of Balanced Resistive Load with NER**

### 5.2.2 Balanced Inductive Load

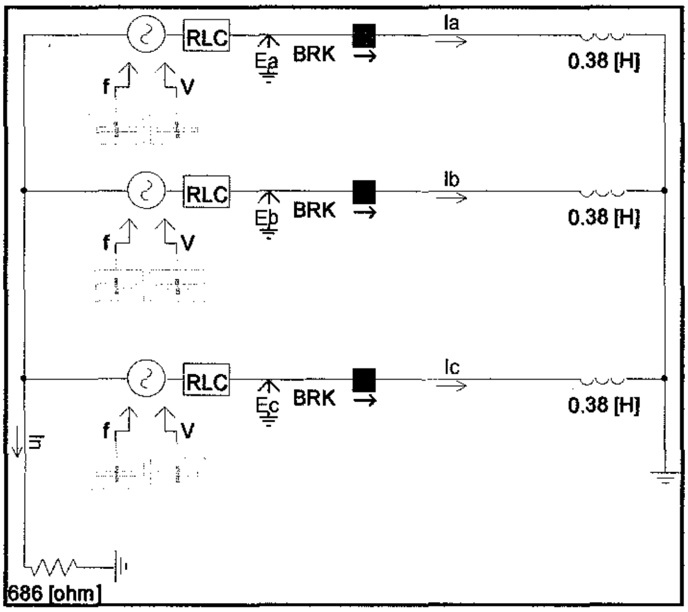



**Figure 164 - Simulation Model of Balanced Inductive Load with NER**

### 5.2.3 Balanced Resistive & Inductive Load

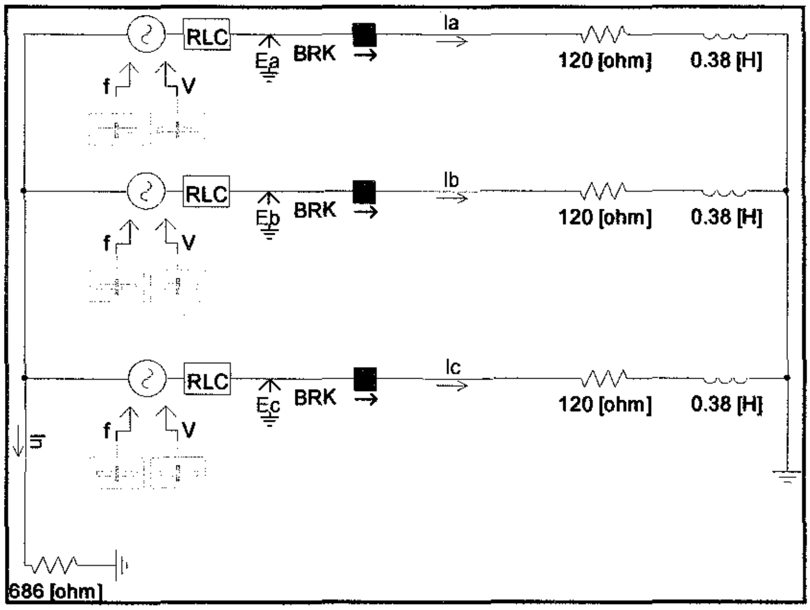



**Figure 165 - Simulation Model of Balanced Resistive & Inductive Load with NER**

## 5.3 Generator with Tuned Peterson Coil

### 5.3.1 Balanced Resistive Load

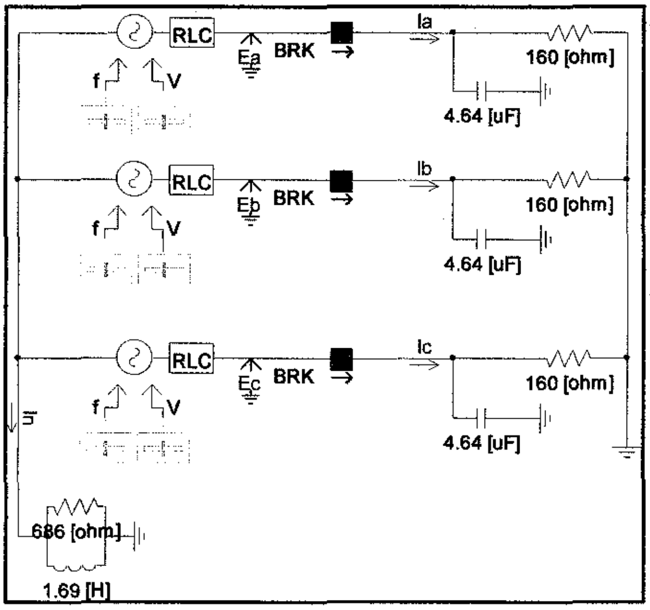



**Figure 166 - Simulation Model of Balanced Resistive Load with Tuned Peterson Coil**

### 5.3.2 Balanced Inductive Load

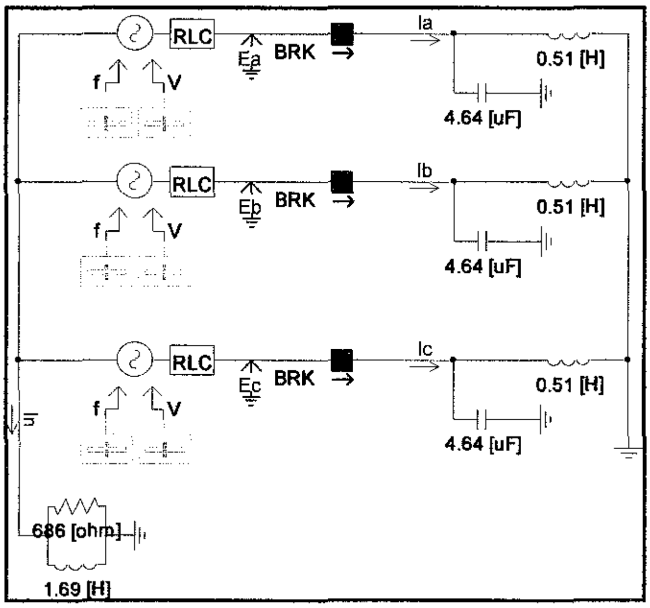



**Figure 167 - Simulation Model of Balanced Inductive Load with Tuned Peterson Coil**

### 5.3.3 Balanced Resistive & Inductive Load

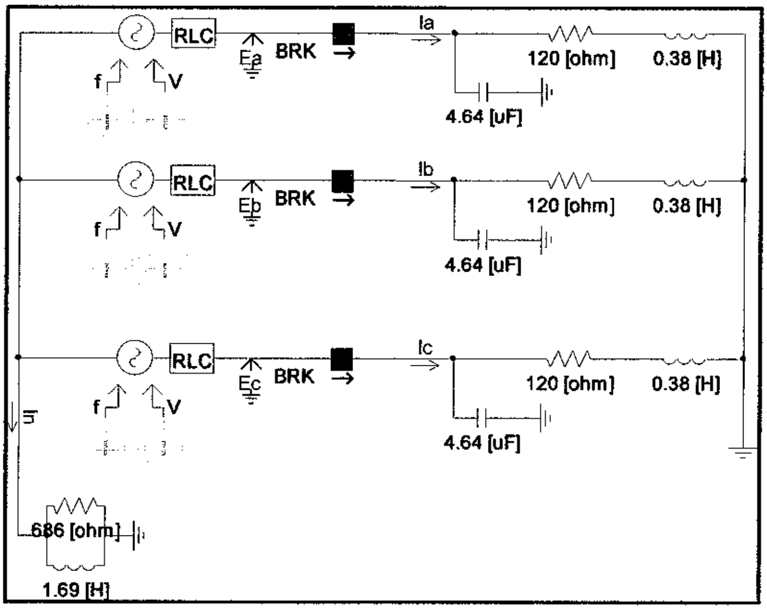



Figure 168 - Simulation Model of Balanced Resistive & Inductive Load with Tuned Peterson Coil

## 5.4 Generator with Untuned Peterson Coil

### 5.4.1 Balanced Resistive Load

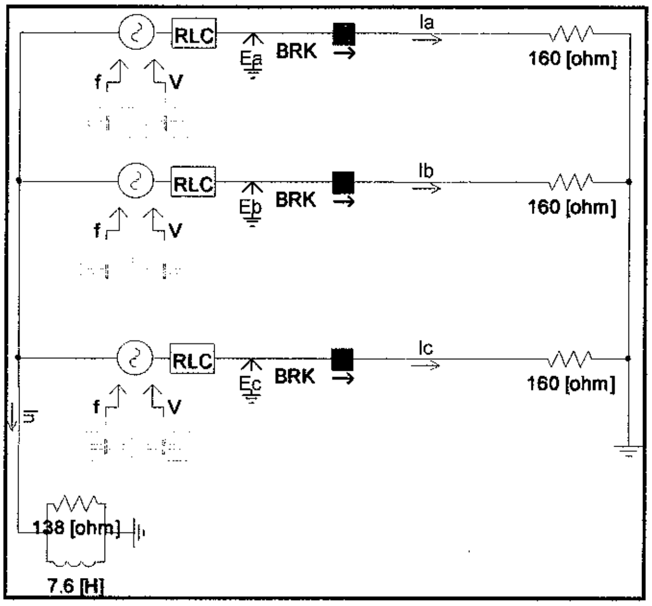



Figure 169 - Simulation Model of Balanced Resistive Load with Untuned Peterson Coil

### 5.4.2 Balanced Inductive Load

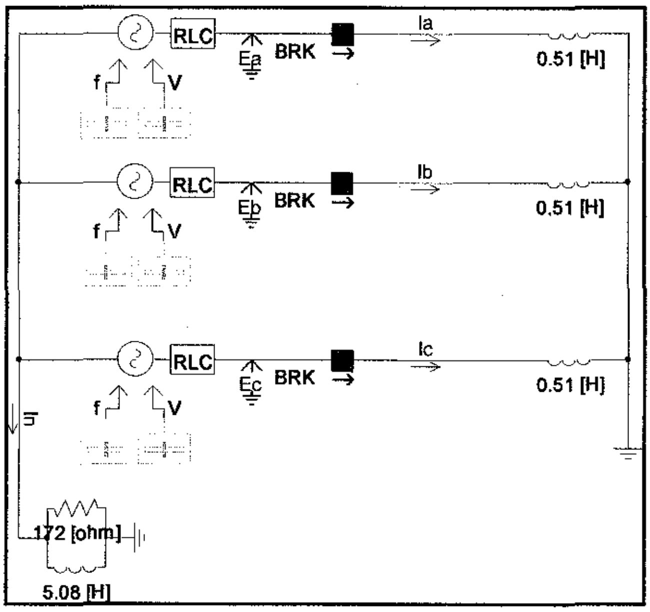



**Figure 170 - Simulation Model of Balanced Inductive Load with Untuned Peterson Coil**

### 5.4.3 Balanced Resistive & Inductive Load

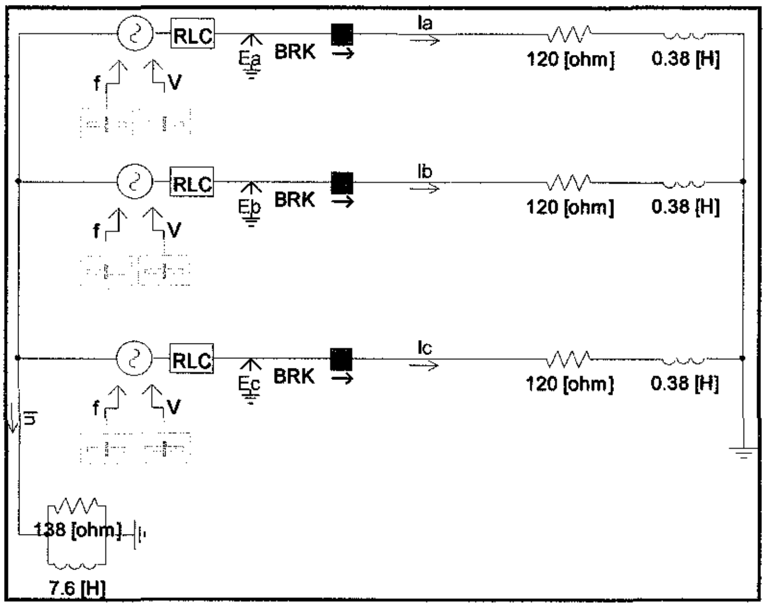



**Figure 171 - Simulation Model of Balanced Resistive & Inductive Load with Untuned Peterson Coil**

## 5.5 Variation Load

### 5.5.1 Balanced Resistive Load

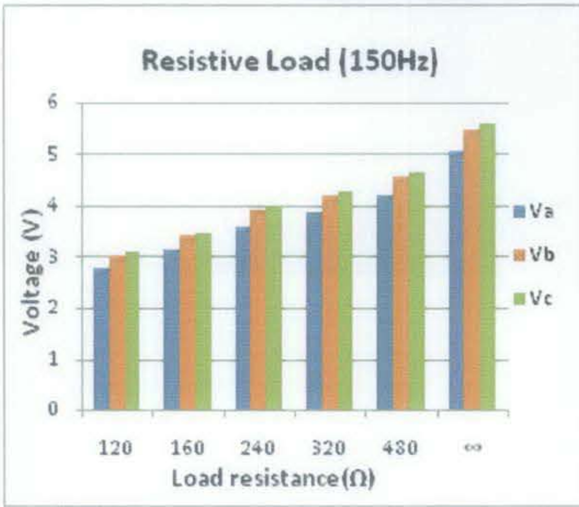



**Figure 172: Third harmonic voltage of balanced resistive load**

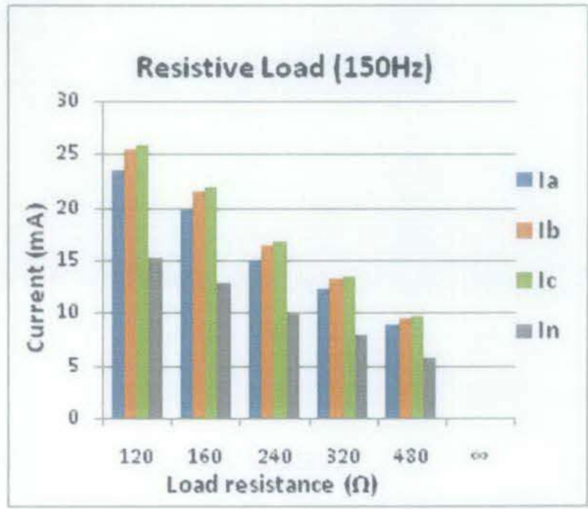



**Figure 173: Third harmonic current of balanced resistive load**

Magnitudes of all phase voltages in figure 172 are approximately same. The voltages are proportional to load impedance. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 173 is almost same. Currents are inversely proportional to load impedance. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with load impedance of 120 ohm are being plotted in phase diagram such in figure 174 and figure 175.

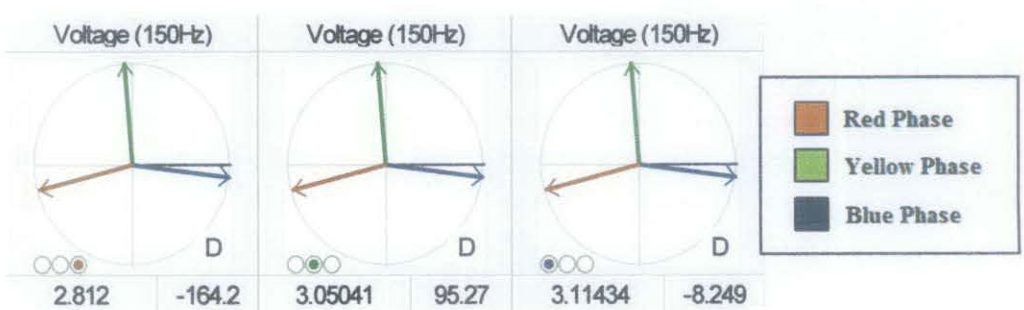



**Figure 174: Fundamental voltage phase angle diagram of balanced resistive load**

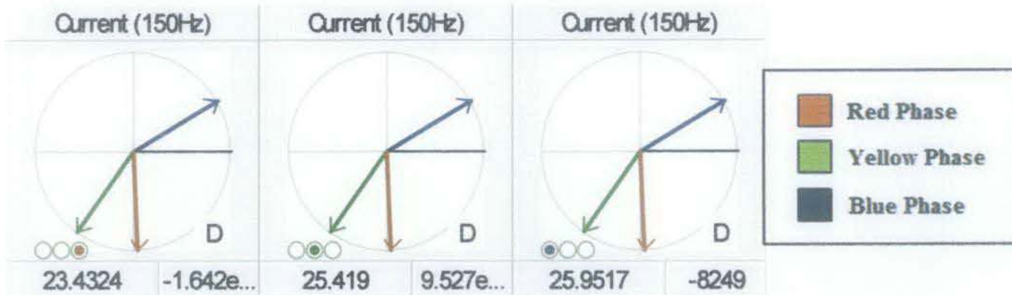



**Figure 175: Third harmonic current phase angle diagram of balanced resistive load**

Table 30 shows the data of voltage and current magnitude for each phase.

**Table 30 – Magnitude of each voltage and current phase for balanced resistive load**

| Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|
| Ω | V | V | V | mA | mA | mA | mA |
| 120 | 2.812 | 3.05 | 3.114 | 23.432 | 25.419 | 25.952 | 15.272 |
| 160 | 3.164 | 3.432 | 3.505 | 19.776 | 21.452 | 21.903 | 12.891 |
| 240 | 3.617 | 3.924 | 4.006 | 15.072 | 16.348 | 16.692 | 9.827 |
| 320 | 3.896 | 4.226 | 4.315 | 12.176 | 13.205 | 13.484 | 7.94 |
| 480 | 4.221 | 4.578 | 4.675 | 8.795 | 9.538 | 9.74 | 5.736 |
| ∞ | 5.066 | 5.493 | 5.611 | 0.005 | 0.005 | 0.006 | 0.003 |

### 5.5.2 Balanced Inductive Load

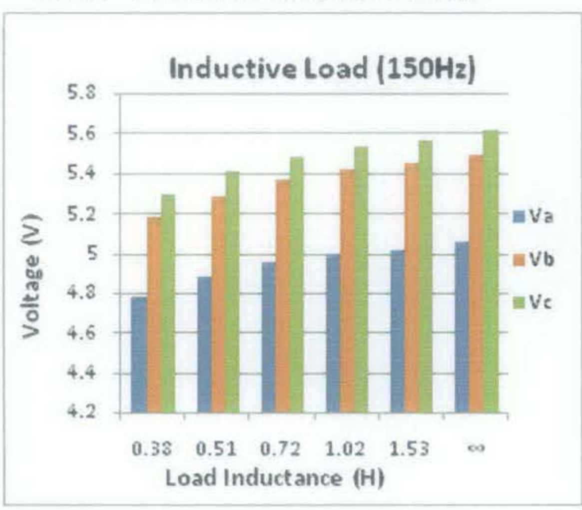



**Figure 176: Third harmonic voltage of balanced inductive load**

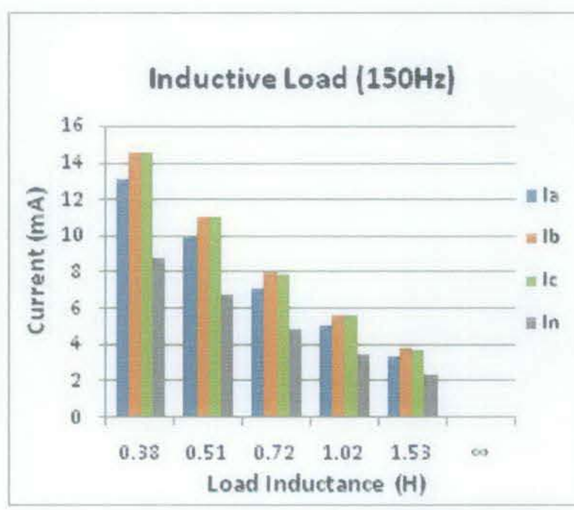



**Figure 177: Third harmonic current of balanced inductive load**

Magnitudes of all phase voltages in figure 176 are different. The voltages magnitudes are proportional to load impedance. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 177 is also different. Currents magnitudes are inversely proportional to load impedance. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with load impedance of 0.38 Henry are being plotted in phase diagram such in figure 178 and figure 179.


**Figure 178: Third harmonic voltage phase angle diagram of balanced inductive load**

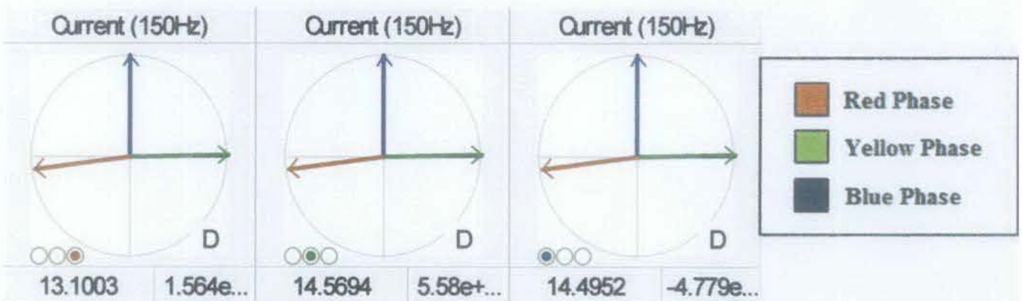



**Figure 179: Third harmonic current phase angle diagram of balanced inductive load**

Table 31 shows the data of voltage and current magnitude for each phase.

**Table 31 - Magnitude of each voltage and current phase for balanced inductive load**

| Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|
| H | V | V | V | mA | mA | mA | mA |
| 0.38 | 4.782 | 5.182 | 5.301 | 13.1 | 14.569 | 14.495 | 8.807 |
| 0.51 | 4.883 | 5.291 | 5.41 | 9.961 | 11.086 | 11.023 | 6.713 |
| 0.72 | 4.954 | 5.369 | 5.487 | 7.155 | 7.968 | 7.919 | 4.835 |
| 1.02 | 4.996 | 5.416 | 5.534 | 5.092 | 5.673 | 5.637 | 3.447 |
| 1.53 | 5.025 | 5.447 | 5.565 | 3.412 | 3.802 | 3.776 | 2.314 |
| ∞ | 5.066 | 5.493 | 5.611 | 0.005 | 0.005 | 0.006 | 0.003 |

### 5.5.3 Balanced Resistive & Inductive Load

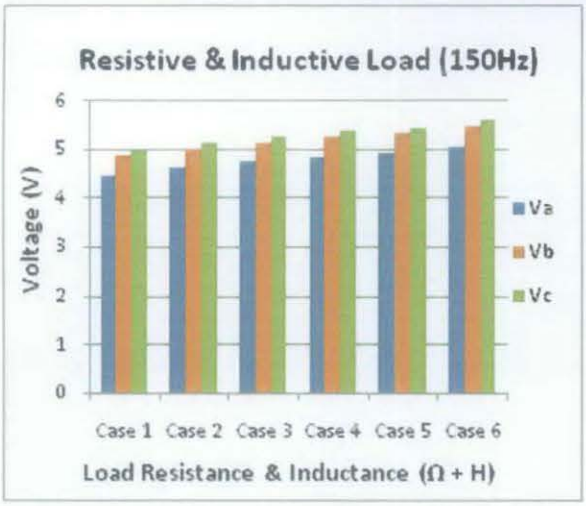



**Figure 180: Third harmonic voltage of balanced resistive & inductive load**

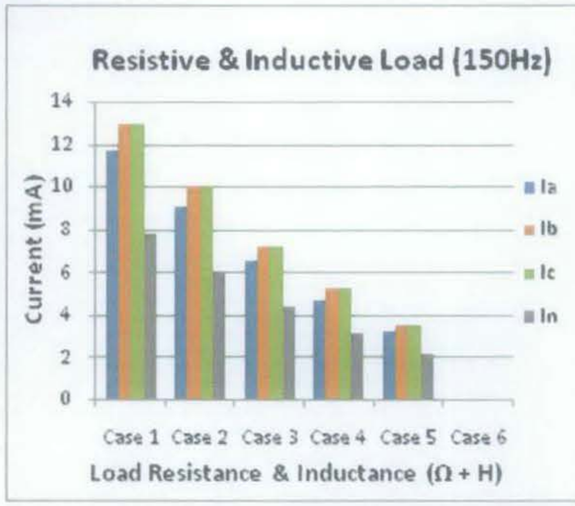



**Figure 181: Third harmonic current of balanced resistive & inductive load**

Magnitudes of all phase voltages in figure 180 are almost equal. The voltages magnitudes are proportional to load impedance. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 181 is also almost same. Currents magnitudes are inversely proportional to load impedance. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with load impedance of 120 ohm and 0.38 Henry are being plotted in phase diagram such in figure 182 and figure 183.

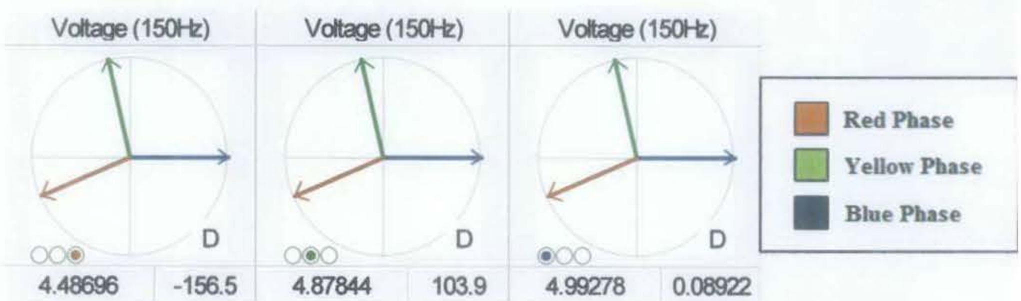



**Figure 182: Third harmonic voltage phase angle diagram of balanced resistive & inductive load**

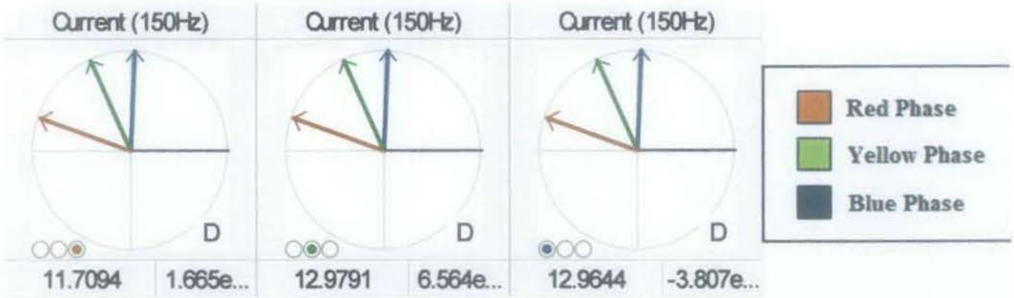



**Figure 183: Third harmonic current phase angle diagram of balanced resistive & inductive load**

Table 32 shows the data of voltage and current magnitude for each phase.

**Table 32 - Magnitude of each voltage and current phase for balanced resistive & inductive load**

| Case | Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|---|
| | Ω + H | V | V | V | mA | mA | mA | mA |
| Case 1 | 120 + 0.38 | 4.487 | 4.878 | 4.993 | 11.709 | 12.979 | 12.964 | 7.764 |
| Case 2 | 160 + 0.51 | 4.65 | 5.04 | 5.158 | 9.022 | 10.005 | 9.986 | 5.996 |
| Case 3 | 240 + 0.72 | 4.769 | 5.169 | 5.287 | 6.511 | 7.224 | 7.206 | 4.334 |
| Case 4 | 320 + 1.02 | 4.865 | 5.274 | 5.392 | 4.717 | 5.236 | 5.22 | 3.147 |
| Case 5 | 480 + 1.53 | 4.934 | 5.35 | 5.467 | 3.189 | 3.541 | 3.529 | 2.13 |
| Case 6 | ∞ | 5.066 | 5.493 | 5.611 | 0.005 | 0.005 | 0.006 | 0.003 |

## 5.6 Generator NER

### 5.6.1 Balanced Resistive Load

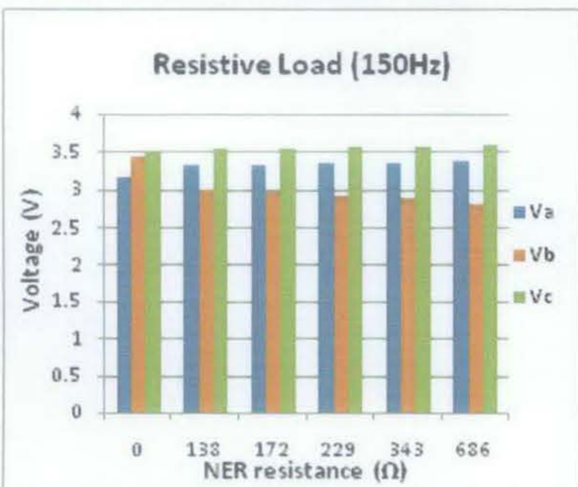



**Figure 184: Third harmonic voltage of balanced resistive load with NER**

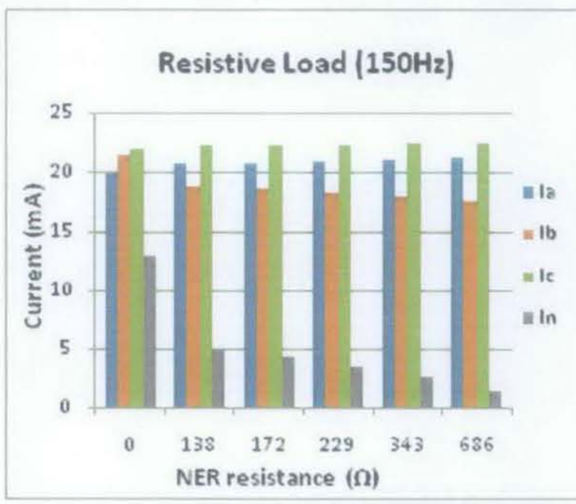



**Figure 185: Third harmonic current of balanced resistive load with NER**

Magnitudes of all phase voltages in figure 184 are different. The voltages magnitudes are proportional to neutral earth resistance (NER). By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 185 is also different. Currents magnitudes are maintain same when neutral earth resistance (NER) increases. Magnitude of neutral phase current is reducing as NER value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no NER are being plotted in phase diagram such in figure 186 and figure 187.


**Figure 186: Third harmonic voltage phase angle diagram of balanced resistive load with NER**

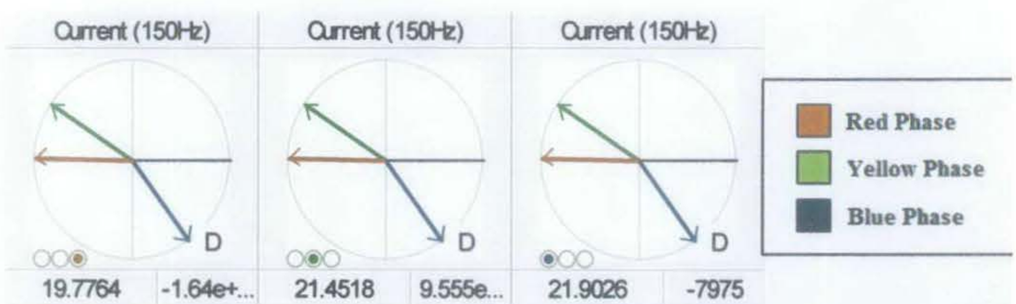



**Figure 187: Third harmonic current phase angle diagram of balanced resistive load with NER**

Table 33 shows the data of voltage and current magnitude for each phase.

**Table 33 - Magnitude of each voltage and current phase for balanced resistive load with NER**

| NER Ω | Load Ω | Va V | Vb V | Vc V | Ia mA | Ib mA | Ic mA | In mA |
|---|---|---|---|---|---|---|---|---|
| 0 | 160 | 3.164 | 3.432 | 3.505 | 19.776 | 21.452 | 21.903 | 12.891 |
| 138 | 160 | 3.312 | 3.005 | 3.547 | 20.699 | 18.781 | 22.171 | 4.932 |
| 172 | 160 | 3.324 | 2.969 | 3.552 | 20.772 | 18.554 | 22.202 | 4.28 |
| 229 | 160 | 3.342 | 2.929 | 3.563 | 20.887 | 18.307 | 22.271 | 3.504 |
| 343 | 160 | 3.364 | 2.881 | 3.577 | 21.027 | 18.008 | 22.358 | 2.572 |
| 686 | 160 | 3.391 | 2.822 | 3.594 | 21.192 | 17.635 | 22.464 | 1.429 |

### 5.6.2 Balanced Inductive Load

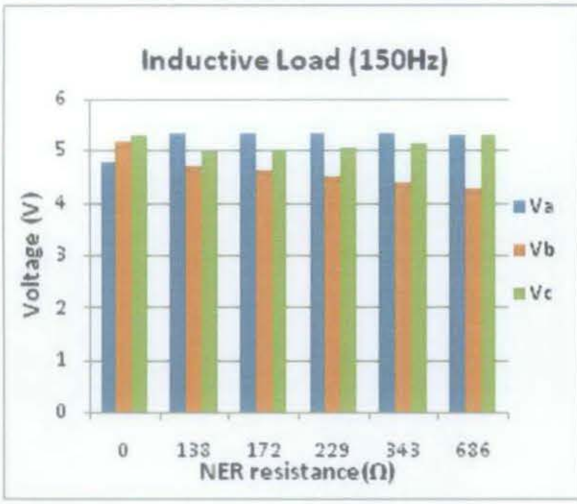



**Figure 188: Third harmonic voltage of balanced inductive load with NER**

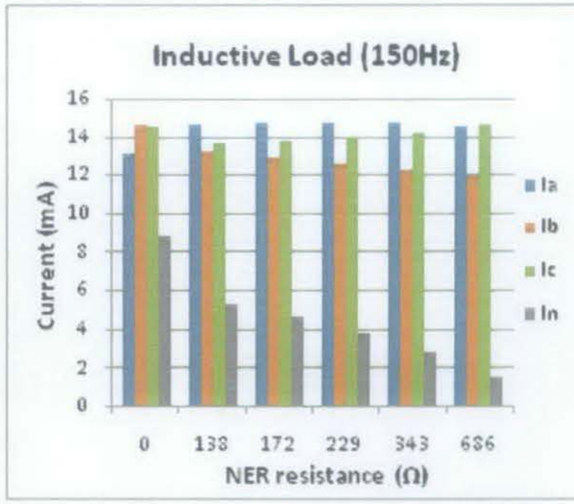



**Figure 189: Third harmonic current of balanced inductive load with NER**

Magnitudes of all phase voltages in figure 188 are different. The voltages magnitudes are same as NER increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 189 is also different. Currents magnitudes are maintain same when neutral earth resistance (NER) increases. Magnitude of neutral phase current is reducing as NER value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no NER are being plotted in phase diagram such in figure 190 and figure 191.


**Figure 190: Third harmonic voltage phase angle diagram of balanced inductive load with NER**

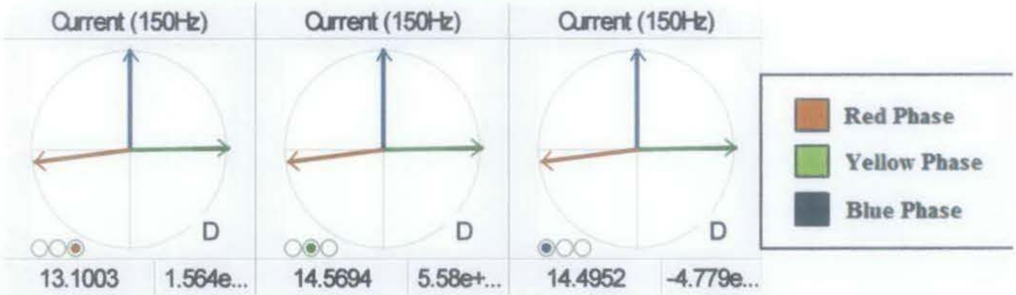



**Figure 191: Third harmonic current phase angle diagram of balanced inductive load with NER**

Table 34 shows the data of voltage and current magnitude for each phase.

**Table 34 - Magnitude of each voltage and current phase for balanced inductive load with NER**

| NER<br>Ω | Load<br>H | Va<br>V | Vb<br>V | Vc<br>V | Ia<br>mA | Ib<br>mA | Ic<br>mA | In<br>mA |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.38 | 4.782 | 5.182 | 5.301 | 13.1 | 14.569 | 14.495 | 8.806 |
| 138 | 0.38 | 5.32 | 4.716 | 4.972 | 14.612 | 13.171 | 13.672 | 5.212 |
| 172 | 0.38 | 5.338 | 4.628 | 5.001 | 14.677 | 12.915 | 13.759 | 4.587 |
| 229 | 0.38 | 5.349 | 4.523 | 5.06 | 14.714 | 12.61 | 13.925 | 3.786 |
| 343 | 0.38 | 5.333 | 4.399 | 5.154 | 14.686 | 12.26 | 14.191 | 2.771 |
| 686 | 0.38 | 5.28 | 4.269 | 5.296 | 14.546 | 11.897 | 14.578 | 1.505 |

### 5.6.3 Balanced Resistive & Inductive Load

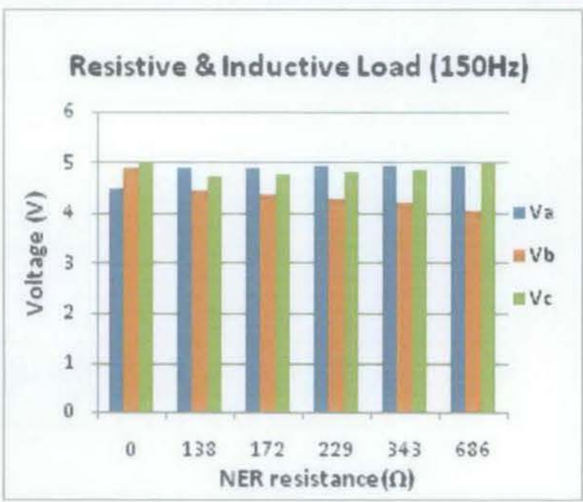



**Figure 192: Third harmonic voltage of balanced resistive & inductive load with NER**

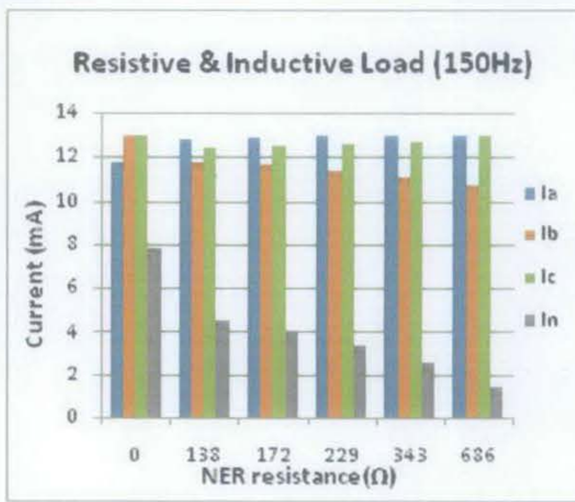



**Figure 193: Third harmonic current of balanced resistive & inductive load with NER**

Magnitudes of all phase voltages in figure 192 are different. The voltages magnitudes are different as NER increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 193 is also different. Currents magnitudes are different when neutral earth resistance (NER) increases. Magnitude of neutral phase current is reducing as NER value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no NER are being plotted in phase diagram such in figure 194 and figure 195.

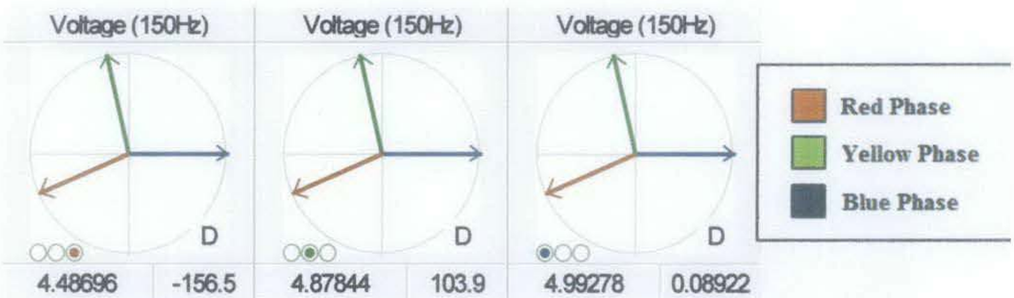



**Figure 194: Third harmonic voltage phase angle diagram of balanced resistive & inductive load with NER**

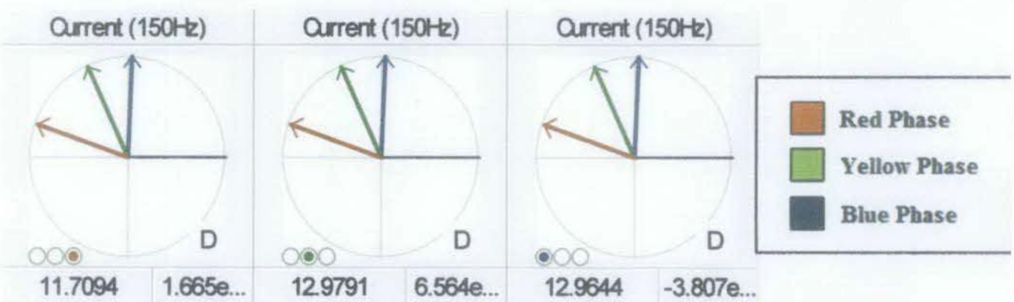



**Figure 195: Third harmonic current phase angle diagram of balanced resistive & inductive load with NER**

Table 35 shows the data of voltage and current magnitude for each phase.

**Table 35 - Magnitude of each voltage and current phase for balanced resistive & inductive load with NER**

| NER<br>Ω | Load<br>Ω + H | Va<br>V | Vb<br>V | Vc<br>V | Ia<br>mA | Ib<br>mA | Ic<br>mA | In<br>mA |
|---|---|---|---|---|---|---|---|---|
| 0 | 120 + 0.38 | 4.487 | 4.878 | 4.993 | 11.709 | 12.979 | 12.964 | 7.764 |
| 138 | 120 + 0.38 | 4.887 | 4.439 | 4.749 | 12.776 | 11.742 | 12.36 | 4.49 |
| 172 | 120 + 0.38 | 4.918 | 4.378 | 4.773 | 12.899 | 11.605 | 12.459 | 3.998 |
| 229 | 120 + 0.38 | 4.942 | 4.295 | 4.811 | 12.952 | 11.365 | 12.549 | 3.361 |
| 343 | 120 + 0.38 | 4.95 | 4.184 | 4.874 | 12.981 | 11.072 | 12.72 | 2.528 |
| 686 | 120 + 0.38 | 4.933 | 4.052 | 4.984 | 12.94 | 10.721 | 13.009 | 1.428 |

## 5.7 Generator with Tuned Peterson Coil

### 5.7.1 Balanced Resistive Load

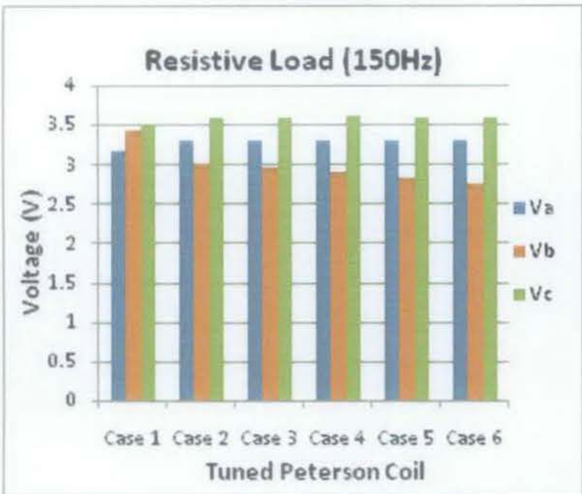



**Figure 196: Third harmonic voltage of balanced resistive load with tuned Peterson coil**

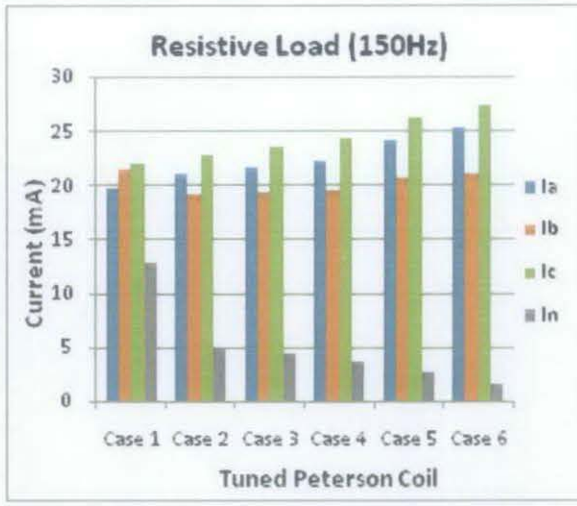



**Figure 197: Third harmonic current of balanced resistive load with tuned Peterson coil**

Magnitudes of all phase voltages in figure 196 are different. The voltages magnitudes are different as Tuned Peterson coil resistance and reactance value increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 197 is also different. Currents magnitudes are proportional to Tuned Peterson Coil value. Magnitude of neutral phase current is reducing as Tuned Peterson Coil resistance and reactance value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no Tuned Peterson Coil are being plotted in phase diagram such in figure 198 and figure 199.

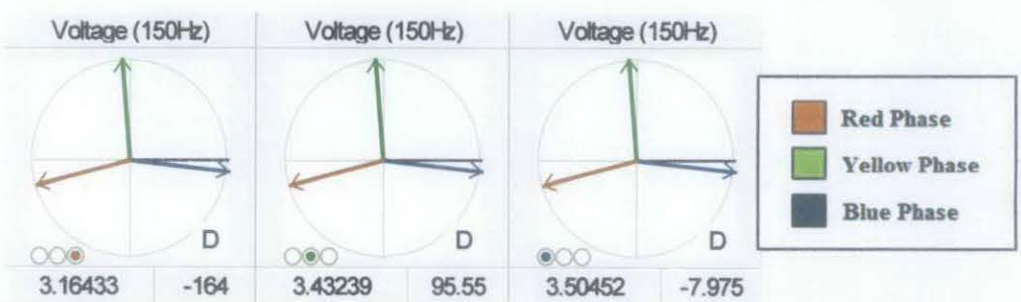



**Figure 198: Third harmonic voltage phase angle diagram of balanced resistive load with tuned Peterson coil**

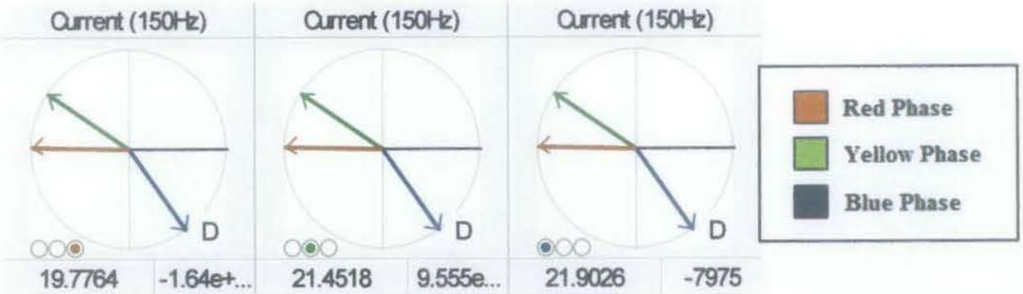



**Figure 199: Third harmonic current phase angle diagram of balanced resistive load with tuned Peterson coil**

Table 36 shows the data of voltage and current magnitude for each phase.

**Table 36 - Magnitude of each voltage and current phase for balanced resistive load with Tuned Peterson Coil**

| Case | Tuned Peterson Coil | Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|---|---|
| | Ω + H + μF | Ω | V | V | V | mA | mA | mA | mA |
| Case 1 | 0 | 160 | 3.164 | 3.432 | 3.505 | 19.776 | 21.452 | 21.903 | 12.891 |
| Case 2 | 138 + 7.6 + 1.33 | 160 | 3.298 | 3.004 | 3.577 | 20.982 | 19.088 | 22.77 | 4.986 |
| Case 3 | 172 + 5.08 + 1.99 | 160 | 3.3 | 2.96 | 3.589 | 21.54 | 19.289 | 23.448 | 4.366 |
| Case 4 | 229 + 3.8 + 2.65 | 160 | 3.303 | 2.907 | 3.595 | 22.249 | 19.532 | 24.248 | 3.607 |
| Case 5 | 343 + 2.53 + 3.98 | 160 | 3.291 | 2.824 | 3.582 | 24.026 | 20.552 | 26.224 | 2.706 |
| Case 6 | 686 + 169 + 4.64 | 160 | 3.295 | 2.748 | 3.574 | 25.192 | 20.931 | 27.401 | 1.619 |

### 5.7.2 Balanced Inductive Load

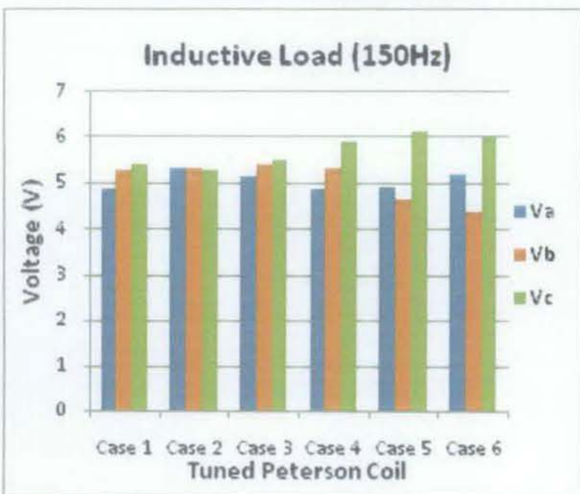



**Figure 200: Third harmonic voltage of balanced inductive load with tuned Peterson coil**

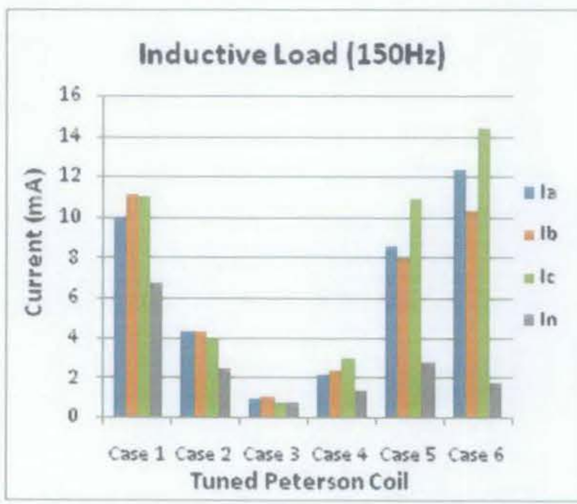



**Figure 201: Third harmonic current of balanced inductive load with tuned Peterson coil**

Magnitudes of all phase voltages in figure 200 are different. The voltages magnitudes are different as Tuned Peterson Coil resistance and reactance value increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 201 is also different. Currents magnitudes are different as Tuned Peterson Coil resistance and reactance value increase. Magnitude of neutral phase current is different as Tuned Peterson Coil resistance and reactance value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no Tuned Peterson Coil are being plotted in phase diagram such in figure 202 and 203.


**Figure 202: Third harmonic voltage phase angle diagram of balanced inductive load with tuned Peterson coil**

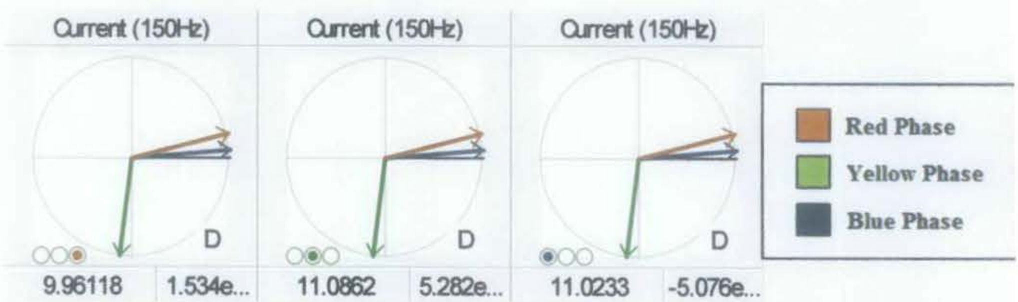



**Figure 203: Third harmonic current phase angle diagram of balanced inductive load with tuned Peterson coil**

Table 37 shows the data of voltage and current magnitude for each phase.

**Table 37 - Magnitude of each voltage and current phase for balanced inductive load with Tuned Peterson Coil**

| Case | Tuned Peterson Coil | Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|---|---|
| | Ω + H + μF | H | V | V | V | mA | mA | mA | mA |
| Case 1 | 0 | 0.51 | 4.883 | 5.291 | 5.41 | 9.961 | 11.086 | 11.023 | 6.713 |
| Case 2 | 138 + 7.6 + 1.33 | 0.51 | 5.33 | 5.329 | 5.276 | 4.24 | 4.319 | 4.003 | 2.41 |
| Case 3 | 172 + 5.08 + 1.99 | 0.51 | 5.166 | 5.431 | 5.517 | 0.918 | 0.973 | 0.671 | 0.667 |
| Case 4 | 229 + 3.8 + 2.65 | 0.51 | 4.881 | 5.338 | 5.911 | 2.177 | 2.382 | 2.996 | 1.344 |
| Case 5 | 343 + 2.53 + 3.98 | 0.51 | 4.954 | 4.665 | 6.161 | 8.547 | 7.977 | 10.877 | 2.704 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case 6 | 686 + 1.69 + 4.64 | 0.51 | 5.217 | 4.39 | 6.01 | 12.283 | 10.294 | 14.386 | 1.777 |

### 5.7.3 Balanced Resistive & Inductive Load

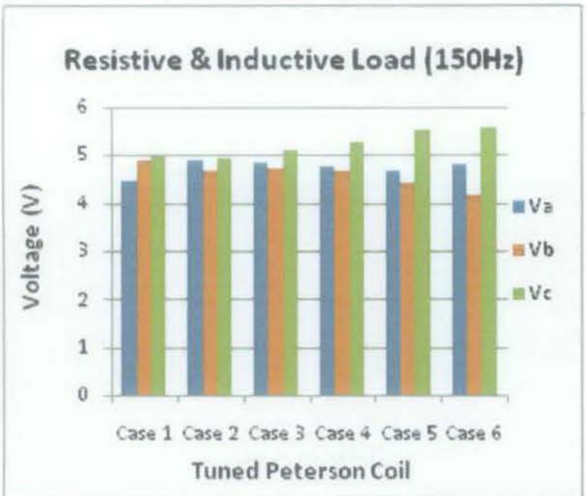



**Figure 204: Third harmonic voltage of balanced resistive & inductive load with tuned Peterson coil**

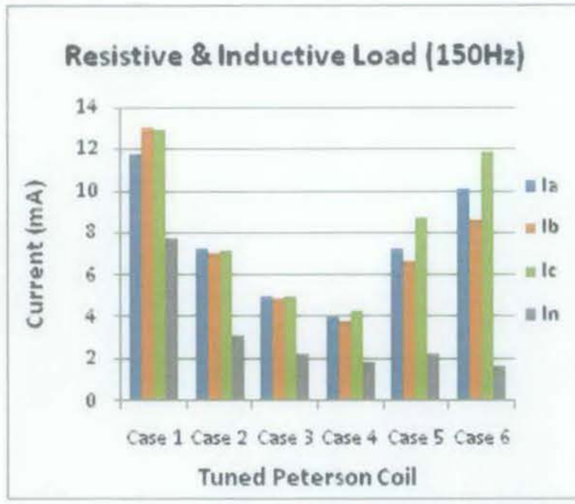



**Figure 205: Third harmonic current of balanced resistive & inductive load with tuned Peterson coil**

Magnitudes of all phase voltages in figure 204 are different. The voltages magnitudes are increasing as Tuned Peterson Coil resistance and reactance value increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 205 is also different. Currents magnitudes are different as Tuned Peterson Coil resistance and reactance value increase. Magnitude of neutral phase current is different as Tuned Peterson Coil resistance and reactance value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no Tuned Peterson Coil are being plotted in phase diagram such in figure 206 and figure 207.

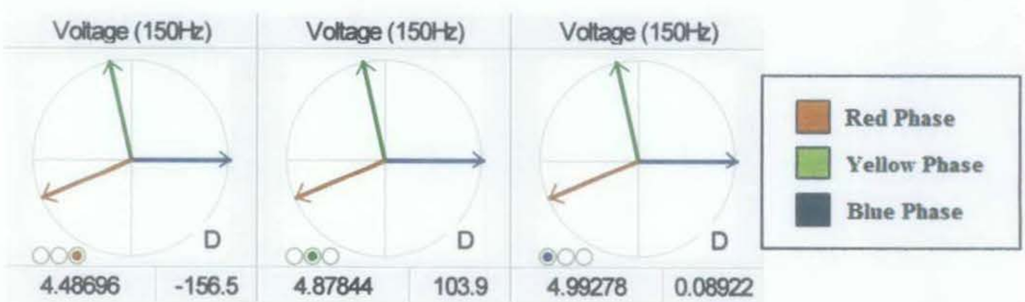



**Figure 206: Third harmonic voltage phase angle diagram of balanced resistive & inductive load with tuned Peterson coil**

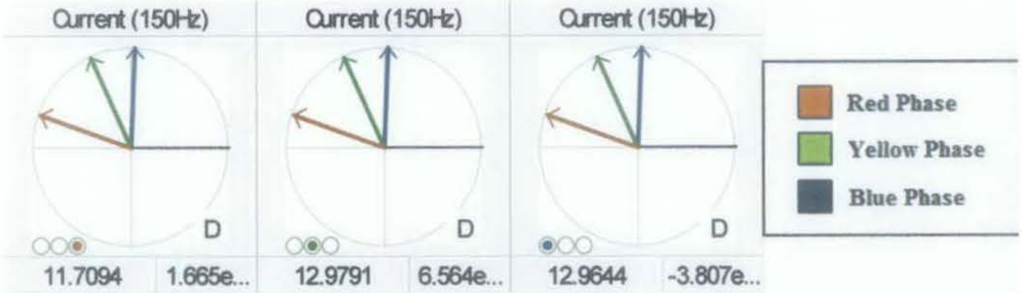



**Figure 207: Third harmonic current phase angle diagram of balanced resistive & inductive load with tuned Peterson coil**

Table 38 shows the data of voltage and current magnitude for each phase.

**Table 38 - Magnitude of each voltage and current phase for balanced resistive & inductive load with Tuned Peterson Coil**

| Case | Tuned Peterson Coil | Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|---|---|
| | Ω + H + μF | Ω + H | V | V | V | mA | mA | mA | mA |
| Case 1 | 0 | 120 + 0.38 | 4.487 | 4.878 | 4.993 | 11.709 | 12.979 | 12.964 | 7.764 |
| Case 2 | 138 + 7.6 + 1.33 | 120 + 0.38 | 4.898 | 4.695 | 4.954 | 7.234 | 7.019 | 7.143 | 3.128 |
| Case 3 | 172 + 5.08 + 1.99 | 120 + 0.38 | 4.862 | 4.731 | 5.086 | 5.004 | 4.851 | 4.993 | 2.242 |
| Case 4 | 229 + 3.8 + 2.65 | 120 + 0.38 | 4.785 | 4.7 | 5.262 | 3.988 | 3.867 | 4.284 | 1.816 |
| Case 5 | 343 + 2.53 + 3.98 | 120 + 0.38 | 4.695 | 4.433 | 5.538 | 7.199 | 6.674 | 8.695 | 2.206 |
| Case 6 | 686 + 1.69 + 4.64 | 120 + 0.38 | 4.825 | 4.173 | 5.558 | 10.118 | 8.579 | 11.826 | 1.616 |

## 5.8 Generator with Untuned Peterson Coil

### 5.8.1 Balanced Resistive Load

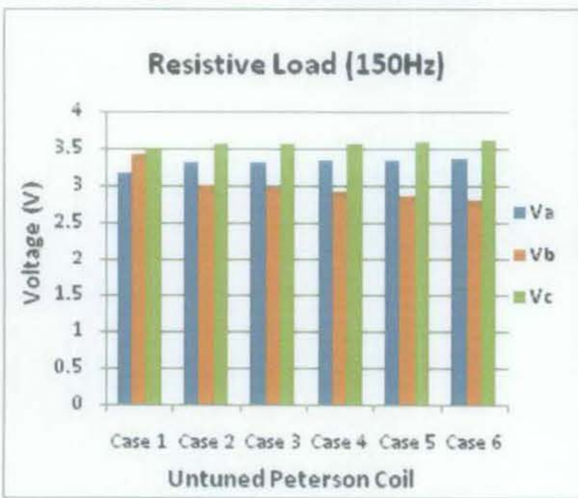



**Figure 208: Third harmonic voltage of balanced resistive load with untuned Peterson coil**

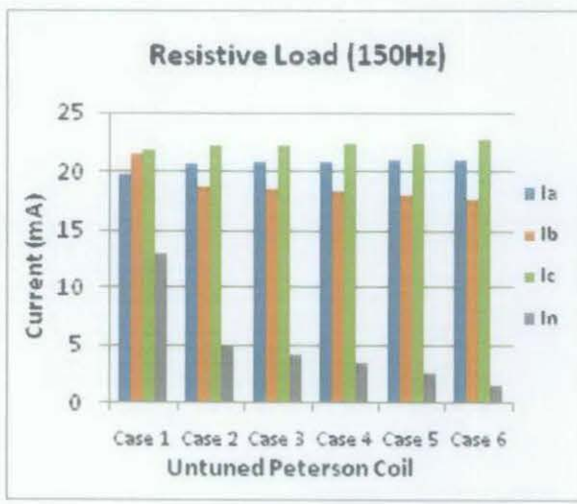



**Figure 209: Third harmonic current of balanced resistive load with untuned Peterson coil**

Magnitudes of all phase voltages in figure 208 are different. The voltages magnitudes are increasing as untuned Peterson coil resistance and reactance value increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 209 is also different. Currents magnitudes are increasing as Tuned Peterson coil resistance and reactance value increase. Magnitude of neutral phase current is reducing as untuned Peterson coil resistance and reactance value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no Untuned Peterson Coil are being plotted in phase diagram such in figure 210 and figure 211.


**Figure 210: Third harmonic voltage phase angle diagram of balanced resistive load with untuned Peterson coil**

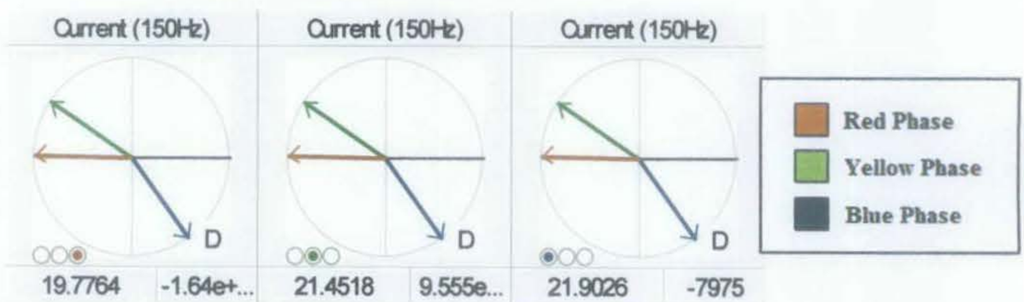



**Figure 211: Third harmonic current phase angle voltage of balanced resistive load with untuned Peterson coil**

Table 39 shows the data of voltage and current magnitude for each phase.

**Table 39 - Magnitude of each voltage and current phase for balanced resistive load with Untuned Peterson Coil**

| ase | Tuned Peterson Coil without capacitor $\Omega$ + H | Load $\Omega$ | Va V | Vb V | Vc V | Ia mA | Ib mA | Ic mA | In mA |
|---|---|---|---|---|---|---|---|---|---|
| se 1 | 0 | 160 | 3.164 | 3.432 | 3.505 | 19.776 | 21.452 | 21.903 | 12.891 |
| se 2 | 138 + 7.6 | 160 | 3.309 | 3.005 | 3.55 | 20.68 | 18.778 | 22.189 | 4.933 |
| se 3 | 172 + 5.08 | 160 | 3.32 | 2.969 | 3.559 | 20.748 | 18.557 | 22.244 | 4.283 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ase 4 | 229 + 3.8 | 160 | 3.333 | 2.928 | 3.571 | 20.833 | 18.297 | 22.321 | 3.51 |
| ase 5 | 343 + 2.53 | 160 | 3.349 | 2.879 | 3.592 | 20.93 | 17.994 | 22.449 | 2.60 |
| ase 6 | 686 + 1.69 | 160 | 3.364 | 2.82 | 3.623 | 21.025 | 17.622 | 22.641 | 1.56 |

### 5.8.2 Balanced Inductive Load

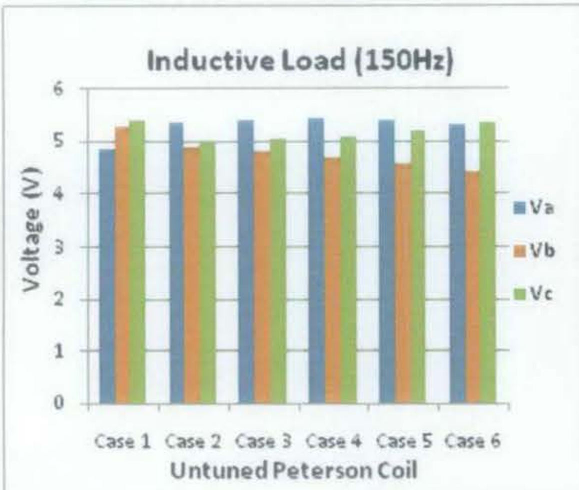



**Figure 212: Third harmonic voltage of balanced inductive load with untuned Peterson coil**

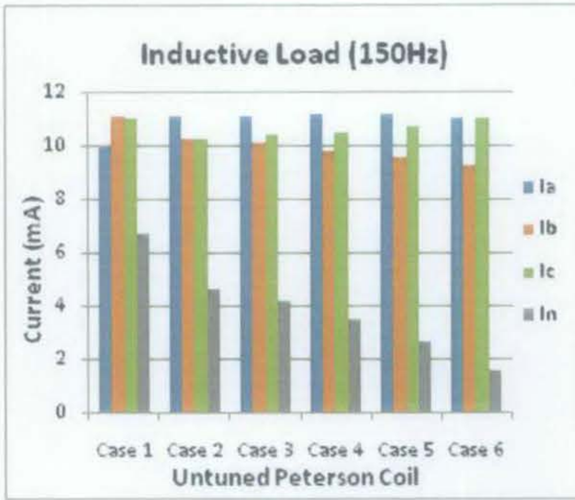



**Figure 213: Third harmonic current of balanced inductive load with untuned Peterson coil**

Magnitudes of all phase voltages in figure 212 are different. The voltages magnitudes are different as untuned Peterson coil resistance and reactance value increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 213 is also different. Currents magnitudes are same as Tuned Peterson coil resistance and reactance value increase. Magnitude of neutral phase current is reducing as untuned Peterson coil resistance and reactance value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no Untuned Peterson Coil are being plotted in phase diagram such in figure 214 and figure 215.


**Figure 214: Third harmonic voltage phase angle diagram of balanced inductive load with untuned Peterson coil**

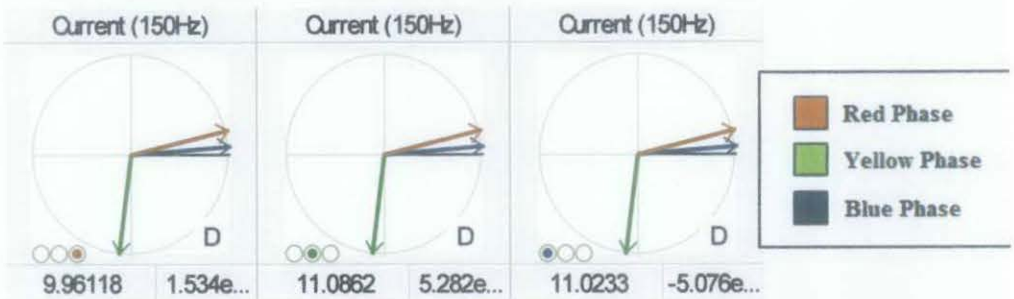



**Figure 215: Third harmonic current phase angle diagram of balanced inductive load with untuned Peterson coil**

Table 40 shows the data of voltage and current magnitude for each phase.

**Table 40 - Magnitude of each voltage and current phase for balanced inductive load with Untuned Peterson Coil**

| ase | Tuned Peterson Coil without capacitor | Load | Va | Vb | Vc | Ia | Ib | Ic | In |
|---|---|---|---|---|---|---|---|---|---|
| | Ω + H | H | V | V | V | mA | mA | mA | mA |
| se 1 | 0 | 0.51 | 4.883 | 5.291 | 5.41 | 9.961 | 11.086 | 11.023 | 6.713 |
| se 2 | 138 + 7.6 | 0.51 | 5.386 | 4.911 | 5.021 | 11.049 | 10.215 | 10.256 | 4.609 |
| se 3 | 172 + 5.08 | 0.51 | 5.433 | 4.836 | 5.054 | 11.115 | 10.066 | 10.36 | 4.128 |
| se 4 | 229 + 3.8 | 0.51 | 5.452 | 4.719 | 5.104 | 11.16 | 9.807 | 10.463 | 3.472 |
| se 5 | 343 + 2.53 | 0.51 | 5.431 | 4.58 | 5.209 | 11.128 | 9.513 | 10.682 | 2.584 |
| se 6 | 686 + 1.69 | 0.51 | 5.346 | 4.444 | 5.373 | 10.964 | 9.237 | 11.021 | 1.504 |

### 5.8.3 Balanced Resistive & Inductive Load

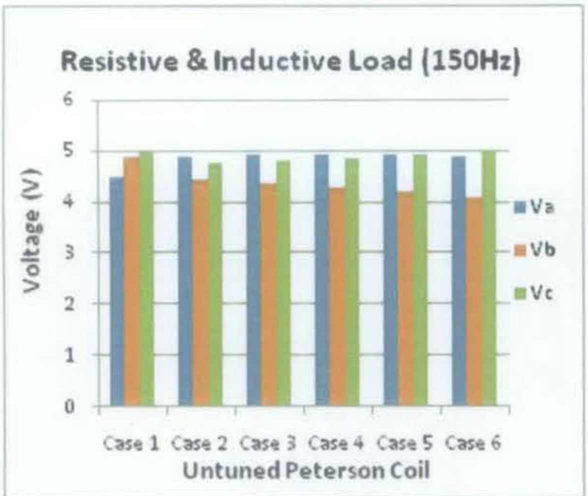



**Figure 216: Third harmonic voltage of balanced resistive & inductive load with untuned Peterson coil**

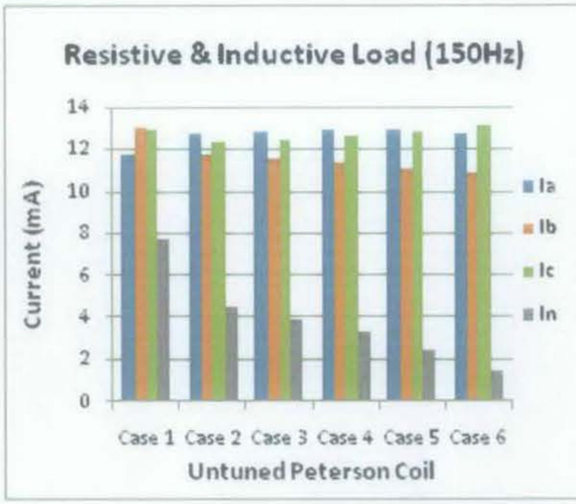



**Figure 217: Third harmonic current of balanced resistive & inductive load with untuned Peterson coil**

Magnitudes of all phase voltages in figure 216 are different. The voltages magnitudes are almost same as untuned Peterson coil resistance and reactance value increase. By using PSCAD software, voltage neutral could not be determined. All phase currents magnitude in figure 217 is also different. Currents magnitudes are almost same as Untuned Peterson coil resistance and reactance value increase. Magnitude of neutral phase current is reducing as untuned Peterson coil resistance and reactance value increase. The third harmonic neutral current is not three times the phase voltage due to positive sequence of phase angle. Examples of phase angle for voltage and current with no Untuned Peterson Coil are being plotted in phase diagram such in figure 218 and figure 219.


**Figure 218: Third harmonic voltage phase angle diagram of balanced resistive & inductive load with untuned Peterson coil**

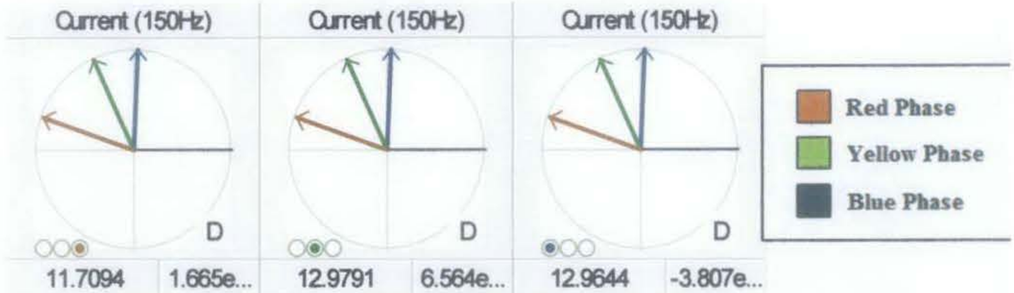



**Figure 219 : Third harmonic current phase angle diagram of balanced resistive & inductive load with untuned Peterson coil**

Table 41 shows the data of voltage and current magnitude for each phase.

**Table 41 - Magnitude of each voltage and current phase for balanced resistive & inductive load with Untuned Peterson Coil**

| se | Tuned Peterson Coil | Load | Va | Vb | Vc | Ia | Ib | Ic | I |
|---|---|---|---|---|---|---|---|---|---|
| | Ω + H | Ω + H | V | V | V | mA | mA | mA | m |
| e 1 | 0 | 120 + 0.38 | 4.487 | 4.878 | 4.993 | 11.709 | 12.979 | 12.964 | 7.7 |
| e 2 | 138 + 7.6 | 120 + 0.38 | 4.881 | 4.438 | 4.755 | 12.761 | 11.74 | 12.376 | 4.4 |
| e 3 | 172 + 5.08 | 120 + 0.38 | 4.907 | 4.377 | 4.783 | 12.863 | 11.598 | 12.48 | 3.9 |
| e 4 | 229 + 3.8 | 120 + 0.38 | 4.923 | 4.295 | 4.827 | 12.894 | 11.363 | 12.583 | 3.3 |
| e 5 | 343 + 2.53 | 120 + 0.38 | 4.915 | 4.195 | 4.901 | 12.889 | 11.104 | 12.79 | 2.4 |
| e 6 | 686 + 1.69 | 120 + 0.38 | 4.871 | 4.086 | 5.018 | 12.771 | 10.82 | 13.095 | 1.4 |

## 5.9 Reason for simulation deviation

Most all the value get from simulation is different from experiment result. This might happen because of:

1. Software that the author use for simulation called PSCAD has no error at all. The equation use to develop for the software has accurate calculation
2. Wrong setting use by the author to set up the simulation. Examples of setting such:
   - Ramp up time
   - Value of resistance, inductance and capacitance
   - Type of source model use
3. Source model that use for software is totally different from source model use by laboratory equipment
4. Measurement accuracy error done by the author during laboratory experiment. Wrong point of measurement may be one of the reason
5. The equipment accuracy itself might be the reason since the laboratory equipment last date of maintenance is during year 2006.

Experiment of parallel between grid and generator could not be simulating by PSCAD. Perhaps that PSCAD is not suitable software use for this type of experiment. Other type of software should be search and use.

# CHAPTER 6

# CONCLUSION

Magnitude of voltage and current produce by synchronous generator is depend on factor such load impedance, generator NER value, Tuned Peterson Coil value and delta configuration.

Generally when high magnitude of load impedance will cause low triplen harmonic currents. Unbalance of equipment impedance can lead triplen harmonic currents to not identical in magnitude and phase angle

The function of generator NER is to reduce earth fault current. Result from experiment also show that generator NER reduce the magnitude of third harmonic neutral current. The higher value of NER applies, the higher neutral current can be reduced.

Main function of Tuned Peterson Coil is to limit the arcing currents during ground faults. However, it can be observed that Tuned Peterson Coil also can reduce triplen harmonic current. Theoretically state that value of impedance for inductance and capacitance of Tuned Peterson Coil should be tuned to be same for Tuned Peterson Coil method to work. So, another experiment of Tuned Peterson Coil in absence of capacitance value is being conducted. The outcome of the experiment tells that without capacitance also Tuned Peterson Coil could reduce triplen harmonic currents.

Under balanced load, triplen harmonic currents are zero sequence in nature. Based on previous journal, it stated delta configuration can block zero sequence networks. However, from the experiment it shows that delta configurations could not block neutral current. So, further study should be conducted regarding delta configuration.

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# APPENDIX A

Equipment details

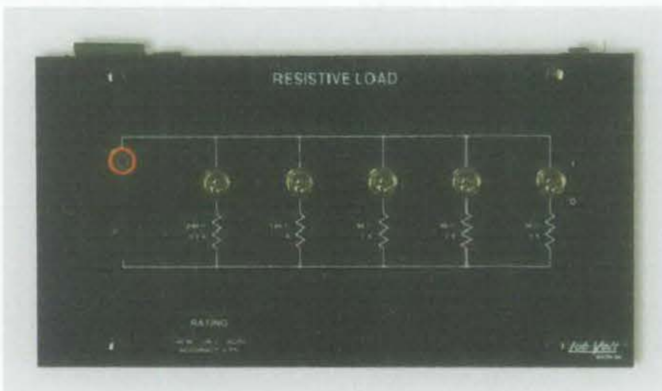
1. Synchronous motor or generator rating (LabVolt EMS 8507-0A)
    - 1500 r/min
    - 240/415 Volts AC
    - 50 Hz
    - 240 VDC
    - Motor ( 2 kW, 0.50 Amps DC)
    - Generator (1.5 kVA, 0.48 Amps DC)
2. DC Motor or generator rating
    - Motor (2 kW, 1500 r/min, 240V, 11A)
    - Generator (1.5 kW, 1500 r/min, 240V, 0.2A)
3. Field rheostat rating
    - 600 Ohm
    - 225W
4. Three phase Transformer rating
    - 250 VA
    - 415/415 V
    - 0.8 A
    - 50 Hz
5. Resistive load rating
    - 1140 W
    - 240 V AC/DC
    - Accuracy +- 5%
6. Tools used :
    - Fluke Power Analyzer
    - Generator
    - Three phase Transformer
    - Resistive load

# APPENDIX B

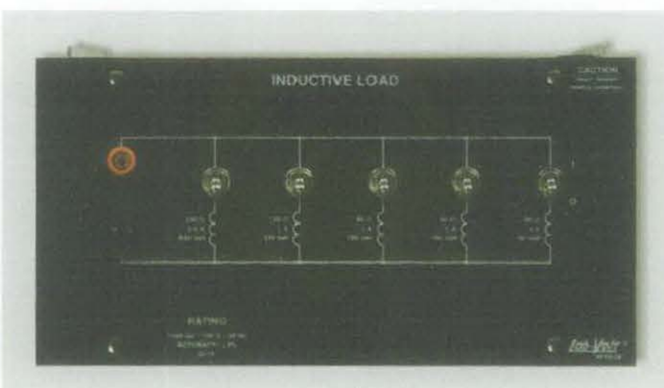
Lab Equipments

Three Phase Synchronous Generator

FLUKE Power Analyzer model 435




Resistive Load




Inductive Load

# APPENDIX C

Experiment result for third harmonic frequency

## Single Generator

### A. Load Variation

**Balanced Resistive Load**

| Load | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| 120 | 150.58 | 2.27 | 150.86 | 3.84 | 151.13 | 3.05 | 151.32 | 1.29 |
| 160 | 149.86 | 2.91 | 149.92 | 4.03 | 149.94 | 3.55 | 149.94 | 0.90 |
| 240 | 150.28 | 3.76 | 150.25 | 4.48 | 150.33 | 4.34 | 150.27 | 0.48 |
| 320 | 151.56 | 4.32 | 151.57 | 4.78 | 151.59 | 4.87 | 151.57 | 0.60 |
| 480 | 150.09 | 4.70 | 150.11 | 5.02 | 150.17 | 5.22 | 150.14 | 0.75 |
| ∞ | 150.92 | 5.03 | 151.00 | 5.53 | 151.14 | 5.61 | 151.34 | 0.94 |

| Load | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| 120 | 150.58 | 19.23 | 150.86 | 30.99 | 151.13 | 25.16 | 151.32 | 17.77 |
| 160 | 149.86 | 17.79 | 149.92 | 24.43 | 149.94 | 21.79 | 149.94 | 10.90 |
| 240 | 150.28 | 15.43 | 150.25 | 17.88 | 150.33 | 17.94 | 150.27 | 5.49 |
| 320 | 151.56 | 13.00 | 151.57 | 14.57 | 151.59 | 14.80 | 151.57 | 3.25 |
| 480 | 150.09 | 9.91 | 150.11 | 10.35 | 150.17 | 11.09 | 150.14 | 1.77 |
| ∞ | 150.92 | 0.29 | 151.00 | 0.29 | 151.14 | 0.48 | 151.34 | 0.84 |

**Balanced Inductive Load**

| Load | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| H | Hz | V | Hz | V | Hz | V | Hz | V |
| 0.38 | 150.37 | 3.94 | 150.38 | 4.21 | 150.39 | 5.06 | 150.47 | 0.85 |
| 0.51 | 150.35 | 4.28 | 150.35 | 4.63 | 150.45 | 5.04 | 150.55 | 0.81 |
| 0.76 | 150.53 | 4.44 | 150.56 | 4.82 | 150.57 | 5.09 | 150.63 | 0.75 |
| 1.02 | 150.48 | 4.71 | 150.44 | 5.15 | 150.45 | 5.51 | 150.50 | 0.56 |
| 1.53 | 150.25 | 4.86 | 150.27 | 5.21 | 150.29 | 5.58 | 150.33 | 0.57 |
| ∞ | 150.92 | 5.03 | 151.00 | 5.53 | 151.14 | 5.61 | 151.34 | 0.94 |

| Load | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| H | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| 0.38 | 150.37 | 43.32 | 150.38 | 38.54 | 150.39 | 60.32 | 150.47 | 140.54 |
| 0.51 | 150.35 | 37.13 | 150.35 | 36.46 | 150.45 | 57.68 | 150.55 | 130.09 |
| 0.76 | 150.53 | 24.18 | 150.56 | 24.19 | 150.57 | 40.58 | 150.63 | 87.66 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1.02 | 150.48 | 16.39 | 150.44 | 16.17 | 150.45 | 25.81 | 150.50 | 56.90 |
| 1.53 | 150.25 | 12.35 | 150.27 | 10.75 | 150.29 | 17.01 | 150.33 | 39.35 |
| ∞ | 150.92 | 0.29 | 151.00 | 0.29 | 151.14 | 0.48 | 151.34 | 0.84 |

**Balanced Resistive & Inductive Load**

| **Load** | **Phase A** | | **Phase B** | | **Phase C** | | **Phase N** | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | V | Hz | V | Hz | V | Hz | V |
| 120+0.38 | 150.46 | 3.54 | 150.57 | 4.15 | 150.63 | 4.13 | 150.80 | 0.25 |
| 160+0.51 | 150.81 | 4.16 | 150.93 | 4.53 | 151.00 | 4.81 | 151.17 | 0.64 |
| 240+0.76 | 150.68 | 4.49 | 150.66 | 4.85 | 150.73 | 5.17 | 150.75 | 1.12 |
| 320+1.02 | 150.01 | 4.62 | 150.06 | 4.96 | 150.09 | 5.22 | 150.22 | 0.33 |
| 480+1.53 | 150.09 | 4.83 | 150.15 | 5.19 | 150.18 | 5.44 | 150.23 | 0.17 |
| ∞ | 150.92 | 5.03 | 151.00 | 5.53 | 151.14 | 5.61 | 151.34 | 0.94 |

| **Load** | **Phase A** | | **Phase B** | | **Phase C** | | **Phase N** | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| 120+0.38 | 150.46 | 25.45 | 150.57 | 39.82 | 150.63 | 34.28 | 150.80 | 97.06 |
| 160+0.51 | 150.81 | 20.11 | 150.93 | 31.81 | 151.00 | 26.74 | 151.17 | 76.63 |
| 240+0.76 | 150.68 | 14.40 | 150.66 | 23.17 | 150.73 | 18.33 | 150.75 | 54.35 |
| 320+1.02 | 150.01 | 7.53 | 150.06 | 13.61 | 150.09 | 8.95 | 150.22 | 28.48 |
| 480+1.53 | 150.09 | 6.35 | 150.15 | 9.89 | 150.18 | 6.19 | 150.23 | 20.73 |
| ∞ | 150.92 | 0.29 | 151.00 | 0.29 | 151.14 | 0.48 | 151.34 | 0.84 |

**B. Generator NER**

**Balanced Resistive Load**

| **NER** | **Phase A** | | **Phase B** | | **Phase C** | | **Phase N** | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 149.86 | 2.91 | 149.92 | 4.03 | 149.94 | 3.55 | 149.94 | 0.90 |
| 138 | 151.44 | 2.97 | 151.50 | 4.10 | 151.50 | 3.59 | 151.50 | 1.24 |
| 172 | 151.24 | 2.94 | 151.29 | 4.12 | 151.24 | 3.60 | 151.29 | 1.21 |
| 229 | 151.15 | 3.06 | 151.12 | 4.10 | 151.13 | 3.49 | 151.20 | 0.75 |
| 343 | 150.97 | 2.97 | 151.02 | 4.12 | 151.11 | 3.58 | 151.14 | 0.84 |
| 686 | 150.62 | 3.06 | 150.69 | 4.06 | 150.74 | 3.55 | 150.91 | 0.92 |

| **NER** | **Phase A** | | **Phase B** | | **Phase C** | | **Phase N** | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 149.86 | 17.79 | 149.92 | 24.43 | 149.94 | 21.79 | 149.94 | 10.90 |
| 138 | 151.44 | 20.11 | 151.50 | 23.13 | 151.50 | 23.83 | 151.50 | 2.75 |
| 172 | 151.24 | 19.51 | 151.29 | 22.92 | 151.24 | 24.01 | 151.29 | 2.44 |
| 229 | 151.15 | 20.75 | 151.12 | 22.17 | 151.13 | 23.09 | 151.20 | 2.11 |
| 343 | 150.97 | 20.50 | 151.02 | 21.75 | 151.11 | 23.93 | 151.14 | 1.77 |

| 686 | 150.62 | 21.32 | 150.69 | 21.69 | 150.74 | 23.36 | 150.91 | 1.07 |
|---|---|---|---|---|---|---|---|---|

**Balanced Inductive Load**

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.37 | 3.94 | 150.38 | 4.21 | 150.39 | 5.06 | 150.47 | 0.85 |
| 138 | 150.26 | 4.08 | 150.39 | 4.17 | 150.45 | 5.00 | 150.48 | 5.18 |
| 172 | 150.66 | 3.93 | 150.69 | 4.10 | 150.79 | 4.93 | 150.84 | 5.36 |
| 229 | 150.61 | 4.02 | 150.64 | 4.11 | 150.67 | 5.05 | 150.74 | 5.86 |
| 343 | 150.79 | 4.06 | 150.80 | 4.11 | 150.85 | 4.97 | 150.90 | 6.33 |
| 686 | 150.59 | 4.02 | 150.64 | 4.06 | 150.64 | 5.06 | 150.66 | 5.58 |

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.37 | 43.32 | 150.38 | 38.54 | 150.39 | 60.32 | 150.47 | 140.54 |
| 138 | 150.26 | 17.04 | 150.39 | 30.30 | 150.45 | 39.54 | 151.13 | 83.33 |
| 172 | 150.66 | 13.48 | 150.69 | 27.96 | 150.79 | 34.55 | 150.84 | 71.07 |
| 229 | 150.61 | 8.87 | 150.64 | 24.09 | 150.67 | 29.68 | 150.74 | 55.82 |
| 343 | 150.79 | 3.50 | 150.80 | 20.14 | 150.85 | 22.76 | 150.90 | 37.39 |
| 686 | 150.59 | 6.69 | 150.64 | 14.79 | 150.64 | 16.38 | 150.66 | 16.44 |

**Balanced Resistive & Inductive Load**

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.46 | 3.54 | 150.57 | 4.15 | 150.63 | 4.13 | 150.80 | 0.25 |
| 138 | 151.78 | 3.56 | 151.82 | 4.07 | 151.83 | 4.19 | 151.89 | 3.19 |
| 172 | 151.40 | 3.67 | 151.48 | 4.04 | 151.53 | 4.33 | 151.60 | 2.88 |
| 229 | 151.26 | 3.46 | 151.32 | 4.11 | 151.37 | 4.21 | 151.39 | 3.64 |
| 343 | 150.62 | 3.42 | 150.67 | 4.09 | 150.89 | 4.28 | 150.93 | 4.25 |
| 686 | 150.02 | 3.48 | 150.04 | 4.05 | 150.02 | 4.22 | 150.06 | 4.78 |

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.46 | 25.45 | 150.57 | 39.82 | 150.63 | 34.28 | 150.80 | 97.06 |
| 138 | 151.78 | 19.15 | 151.82 | 27.05 | 151.83 | 15.11 | 151.89 | 55.06 |
| 172 | 151.40 | 18.12 | 151.48 | 24.37 | 151.53 | 12.97 | 151.60 | 47.54 |
| 229 | 151.26 | 16.54 | 151.32 | 21.40 | 151.37 | 9.09 | 151.39 | 38.12 |
| 343 | 150.62 | 13.04 | 150.67 | 12.16 | 150.89 | 7.79 | 150.93 | 26.40 |
| 686 | 150.02 | 12.80 | 150.04 | 12.58 | 150.02 | 7.99 | 150.06 | 12.20 |

## C. Tuned Peterson Coil
### Balanced Resistive Load

| Tuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H + μF | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 149.86 | 2.91 | 149.92 | 4.03 | 149.94 | 3.55 | 149.94 | 0.90 |
| 138 + 7.6 + 1.33 | 150.47 | 3.06 | 150.55 | 4.32 | 150.65 | 3.74 | 150.79 | 1.26 |
| 172 + 5.08 + 1.99 | 150.94 | 3.18 | 151.04 | 4.45 | 151.13 | 3.85 | 151.19 | 1.16 |
| 229 + 3.8 + 2.65 | 150.49 | 3.28 | 150.58 | 4.45 | 150.57 | 3.93 | 150.61 | 0.46 |
| 343 + 2.53 + 3.98 | 150.57 | 3.39 | 150.60 | 4.68 | 150.60 | 4.07 | 150.69 | 0.86 |
| 686 + 169 + 4.64 | 151.01 | 3.40 | 151.04 | 4.81 | 151.08 | 4.18 | 151.12 | 0.37 |

| Tuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H + μF | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 149.86 | 17.79 | 149.92 | 24.43 | 149.94 | 21.79 | 149.94 | 10.90 |
| 138 + 7.6 + 1.33 | 150.47 | 21.21 | 150.55 | 24.61 | 150.65 | 24.83 | 150.79 | 3.31 |
| 172 + 5.08 + 1.99 | 150.94 | 22.82 | 151.04 | 25.82 | 151.13 | 25.92 | 151.19 | 2.32 |
| 229 + 3.8 + 2.65 | 150.49 | 24.14 | 150.58 | 26.87 | 150.57 | 27.25 | 150.61 | 2.13 |
| 343 + 2.53 + 3.98 | 150.57 | 26.85 | 150.60 | 30.41 | 150.60 | 30.14 | 150.69 | 1.93 |
| 686 + 169 + 4.64 | 151.01 | 28.85 | 151.04 | 33.23 | 151.08 | 32.58 | 151.12 | 1.37 |

### Balanced Inductive Load

| Tuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H + μF | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.35 | 4.28 | 150.35 | 4.63 | 150.45 | 5.04 | 150.55 | 1.08 |
| 138 + 7.6 + 1.33 | 150.24 | 4.63 | 150.20 | 4.85 | 150.21 | 5.29 | 150.18 | 3.54 |
| 172 + 5.08 + 1.99 | 150.06 | 4.79 | 150.09 | 4.95 | 150.13 | 5.39 | 150.18 | 3.55 |
| 229 + 3.8 + 2.65 | 150.15 | 4.86 | 150.15 | 5.02 | 150.15 | 5.41 | 150.18 | 4.35 |
| 343 + 2.53 + 3.98 | 150.14 | 5.61 | 150.15 | 5.44 | 150.14 | 6.04 | 150.14 | 5.87 |
| 686 + 169 + 4.64 | 150.18 | 5.86 | 150.20 | 5.76 | 150.19 | 6.65 | 150.17 | 6.12 |

| Tuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H + μF | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.35 | 37.13 | 150.35 | 36.46 | 150.45 | 57.68 | 150.55 | 130.09 |
| 138 + 7.6 + 1.33 | 150.24 | 25.24 | 150.20 | 28.59 | 150.21 | 36.89 | 150.18 | 89.82 |
| 172 + 5.08 + 1.99 | 150.06 | 24.13 | 150.09 | 22.78 | 150.13 | 30.23 | 150.18 | 78.75 |
| 229 + 3.8 + 2.65 | 150.15 | 22.68 | 150.15 | 16.83 | 150.15 | 22.17 | 150.18 | 63.34 |
| 343 + 2.53 + 3.98 | 150.14 | 23.37 | 150.15 | 7.99 | 150.14 | 12.81 | 150.14 | 42.81 |
| 686 + 169 + 4.64 | 150.18 | 19.78 | 150.20 | 9.96 | 150.19 | 9.22 | 150.17 | 21.16 |

**Balanced Resistive & Inductive Load**

| Tuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H + μF | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.46 | 3.54 | 150.57 | 4.15 | 150.63 | 4.13 | 150.80 | 0.25 |
| 138 + 7.6 + 1.33 | 151.01 | 3.78 | 151.10 | 4.28 | 151.09 | 4.48 | 151.10 | 3.20 |
| 172 + 5.08 + 1.99 | 150.78 | 3.84 | 150.79 | 4.40 | 150.87 | 4.59 | 150.86 | 3.45 |
| 229 + 3.8 + 2.65 | 150.79 | 3.98 | 150.85 | 4.48 | 150.87 | 4.70 | 150.89 | 3.40 |
| 343 + 2.53 + 3.98 | 150.52 | 4.22 | 150.51 | 4.92 | 150.54 | 5.28 | 150.59 | 3.23 |
| 686 + 169 + 4.64 | 150.21 | 4.27 | 150.25 | 5.03 | 150.27 | 5.41 | 150.36 | 4.41 |

| Tuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H + μF | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.46 | 25.45 | 150.57 | 39.82 | 150.63 | 34.28 | 150.80 | 97.06 |
| 138 + 7.6 + 1.33 | 151.01 | 16.48 | 151.10 | 22.76 | 151.09 | 17.32 | 151.10 | 54.48 |
| 172 + 5.08 + 1.99 | 150.78 | 12.69 | 150.79 | 17.93 | 150.87 | 15.57 | 150.86 | 46.70 |
| 229 + 3.8 + 2.65 | 150.79 | 9.94 | 150.85 | 12.82 | 150.87 | 15.01 | 150.89 | 37.41 |
| 343 + 2.53 + 3.98 | 150.52 | 3.26 | 150.51 | 8.85 | 150.54 | 15.64 | 150.59 | 25.92 |
| 686 + 169 + 4.64 | 150.21 | 5.11 | 150.25 | 9.39 | 150.27 | 15.05 | 150.36 | 13.21 |

## D. Untuned Peterson Coil

**Balanced Resistive Load**

| Untuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.14 | 2.96 | 150.29 | 4.12 | 150.36 | 3.52 | 150.48 | 0.87 |
| 138 + 7.6 | 150.91 | 2.96 | 150.92 | 4.05 | 150.89 | 3.57 | 150.98 | 1.12 |
| 172 + 5.08 | 150.95 | 2.98 | 150.93 | 4.12 | 150.96 | 3.61 | 151.02 | 1.13 |
| 229 + 3.8 | 150.61 | 2.97 | 150.65 | 4.04 | 150.65 | 3.61 | 150.74 | 1.20 |
| 343 + 2.53 | 150.89 | 2.95 | 150.91 | 4.03 | 150.93 | 3.62 | 150.96 | 0.76 |
| 686 + 169 | 151.07 | 3.05 | 151.12 | 4.10 | 151.13 | 3.60 | 151.09 | 1.19 |

| Untuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.14 | 18.54 | 150.29 | 25.56 | 150.36 | 22.27 | 150.48 | 11.02 |
| 138 + 7.6 | 150.91 | 20.00 | 150.92 | 22.60 | 150.89 | 23.61 | 150.98 | 3.33 |
| 172 + 5.08 | 150.95 | 20.29 | 150.93 | 22.91 | 150.96 | 23.44 | 151.02 | 2.73 |
| 229 + 3.8 | 150.61 | 20.32 | 150.65 | 22.31 | 150.65 | 23.74 | 150.74 | 2.32 |
| 343 + 2.53 | 150.89 | 20.30 | 150.91 | 22.08 | 150.93 | 23.95 | 150.96 | 1.57 |
| 686 + 169 | 151.07 | 20.76 | 151.12 | 22.18 | 151.13 | 24.04 | 151.09 | 0.92 |

**Balanced Inductive Load**

| Untuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.31 | 4.30 | 150.29 | 4.79 | 150.30 | 5.36 | 150.30 | 0.98 |
| 138 + 7.6 | 150.88 | 4.34 | 150.87 | 4.83 | 150.90 | 5.31 | 150.89 | 3.95 |
| 172 + 5.08 | 150.80 | 4.42 | 150.77 | 4.72 | 150.82 | 5.35 | 150.84 | 4.60 |
| 229 + 3.8 | 150.30 | 4.38 | 150.35 | 4.74 | 150.36 | 5.41 | 150.38 | 5.89 |
| 343 + 2.53 | 150.11 | 4.29 | 150.17 | 4.83 | 150.24 | 5.44 | 150.27 | 4.93 |
| 686 + 169 | 150.30 | 4.34 | 150.31 | 4.73 | 150.34 | 5.31 | 150.30 | 5.88 |

| Untuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.31 | 36.86 | 150.29 | 41.57 | 150.30 | 53.58 | 150.30 | 131.71 |
| 138 + 7.6 | 150.88 | 20.48 | 150.87 | 33.94 | 150.90 | 38.97 | 150.89 | 91.90 |
| 172 + 5.08 | 150.80 | 17.51 | 150.77 | 30.41 | 150.82 | 34.79 | 150.84 | 81.29 |
| 229 + 3.8 | 150.30 | 12.45 | 150.35 | 26.76 | 150.36 | 30.12 | 150.38 | 67.75 |
| 343 + 2.53 | 150.11 | 7.54 | 150.17 | 21.47 | 150.24 | 24.22 | 150.27 | 49.22 |
| 686 + 169 | 150.30 | 2.48 | 150.31 | 14.70 | 150.34 | 17.23 | 150.30 | 27.92 |

**Balanced Resistive & Inductive Load**

| Untuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.34 | 3.61 | 150.35 | 4.10 | 150.41 | 4.34 | 150.37 | 1.19 |
| 138 + 7.6 | 150.39 | 3.62 | 150.36 | 4.04 | 150.42 | 4.41 | 150.47 | 1.98 |
| 172 + 5.08 | 150.82 | 3.68 | 150.88 | 4.15 | 150.82 | 4.41 | 150.89 | 2.93 |
| 229 + 3.8 | 150.89 | 3.74 | 150.89 | 4.05 | 150.94 | 4.41 | 150.99 | 3.27 |
| 343 + 2.53 | 151.23 | 3.66 | 151.32 | 4.16 | 151.29 | 4.42 | 151.32 | 2.94 |
| 686 + 169 | 151.33 | 3.60 | 151.30 | 4.13 | 151.33 | 4.30 | 151.38 | 3.22 |

| Untuned Peterson Coil | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω + H | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.34 | 24.09 | 150.35 | 42.55 | 150.41 | 36.99 | 150.37 | 100.33 |
| 138 + 7.6 | 150.39 | 17.44 | 150.36 | 28.92 | 150.42 | 16.95 | 150.47 | 56.31 |
| 172 + 5.08 | 150.82 | 16.81 | 150.88 | 26.95 | 150.82 | 13.92 | 150.89 | 49.16 |
| 229 + 3.8 | 150.89 | 15.34 | 150.89 | 23.33 | 150.94 | 11.48 | 150.99 | 40.42 |
| 343 + 2.53 | 151.23 | 13.59 | 151.32 | 20.67 | 151.29 | 9.91 | 151.32 | 29.87 |
| 686 + 169 | 151.33 | 11.57 | 151.30 | 16.44 | 151.33 | 9.42 | 151.38 | 17.34 |

E. **Delta Configuration**
**Balanced Inductive Load (Delta-Star Configuration)**

| Measurement Point | Voltage (V) | | | | Phase Angle | | | |
|---|---|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Neutral | Phase A | Phase B | Phase C | Neutral |
| Generator | 4.12 | 4.42 | 5.30 | 0.69 | -113.73 | -229.18 | -347.27 | -80.60 |
| TX Primary | 4.16 | 4.45 | 5.30 | | -114.06 | -229.19 | -346.40 | |
| TX Secondary | 4.98 | 5.17 | 3.46 | 0.62 | 156.65 | -295.75 | -83.53 | -279.18 |
| Load | 4.93 | 5.18 | 3.37 | 0.60 | 155.52 | -295.51 | -84.52 | -276.20 |

| Measurement Point | Current (mA) | | | | Phase Angle | | | |
|---|---|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Neutral | Phase A | Phase B | Phase C | Neutral |
| Generator | 10.72 | 11.28 | 12.12 | 11.61 | -205.58 | -309.71 | -77.48 | -130.67 |
| TX Primary | 39.26 | 33.55 | 44.57 | | -158.09 | 31.81 | -324.00 | |
| TX Secondary | 30.23 | 50.26 | 49.11 | 128.14 | -82.22 | -78.13 | -102.28 | -268.70 |
| Load | 30.41 | 50.19 | 48.98 | 0.03 | -82.46 | -78.16 | -103.17 | -191.98 |

## Parallel between Grid and Generator

A. **Generator NER**
**Balanced Inductive Load**
**Generator Side**

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.04 | 0.29 | 150.04 | 0.13 | 150.04 | 0.22 | 149.99 | 0.50 |
| 138 | 150.02 | 0.29 | 150.03 | 0.24 | 150.04 | 0.31 | 150.04 | 4.10 |
| 172 | 149.98 | 0.36 | 150.05 | 0.21 | 150.00 | 0.23 | 150.02 | 4.36 |
| 229 | 150.03 | 0.26 | 149.98 | 0.32 | 150.04 | 0.26 | 150.03 | 4.67 |
| 343 | 150.01 | 0.22 | 150.01 | 0.25 | 150.04 | 0.19 | 149.99 | 4.83 |
| 686 | 150.05 | 0.23 | 150.02 | 0.35 | 150.03 | 0.21 | 150.02 | 4.96 |

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.04 | 21.25 | 150.04 | 31.67 | 150.04 | 26.80 | 149.99 | 53.32 |
| 138 | 150.02 | 26.61 | 150.03 | 28.47 | 150.04 | 17.46 | 150.04 | 42.56 |
| 172 | 149.98 | 27.04 | 150.05 | 24.71 | 150.00 | 15.03 | 150.02 | 34.92 |
| 229 | 150.03 | 27.50 | 149.98 | 21.29 | 150.04 | 15.70 | 150.03 | 26.86 |
| 343 | 150.01 | 24.77 | 150.01 | 19.74 | 150.04 | 16.45 | 149.99 | 22.55 |
| 686 | 150.05 | 22.18 | 150.02 | 23.46 | 150.03 | 19.27 | 150.02 | 24.15 |

**Grid Side**

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.06 | 0.29 | 149.96 | 0.22 | 150.05 | 0.22 | 150.03 | 0.50 |
| 138 | 150.01 | 0.27 | 150.04 | 0.36 | 150.02 | 0.29 | 150.03 | 4.04 |
| 172 | 150.05 | 0.24 | 150.01 | 0.30 | 150.03 | 0.26 | 150.04 | 4.35 |
| 229 | 150.02 | 0.20 | 150.05 | 0.25 | 150.01 | 0.29 | 150.02 | 4.58 |
| 343 | 149.99 | 0.27 | 150.01 | 0.32 | 150.02 | 0.21 | 150.01 | 4.78 |
| 686 | 149.95 | 0.23 | 150.02 | 0.30 | 149.93 | 0.22 | 150.03 | 4.95 |

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.06 | 49.14 | 149.96 | 16.65 | 150.05 | 30.90 | 150.03 | 86.16 |
| 138 | 150.01 | 18.20 | 150.04 | 27.48 | 150.02 | 36.65 | 150.03 | 53.34 |
| 172 | 150.05 | 21.36 | 150.01 | 24.22 | 150.03 | 34.61 | 150.04 | 47.21 |
| 229 | 150.02 | 15.30 | 150.05 | 25.36 | 150.01 | 31.34 | 150.02 | 38.09 |
| 343 | 149.99 | 15.21 | 150.01 | 27.55 | 150.02 | 28.79 | 150.01 | 36.80 |
| 686 | 149.95 | 8.80 | 150.02 | 22.93 | 149.93 | 26.63 | 150.03 | 33.58 |

**Load Side**

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | V | Hz | V | Hz | V | Hz | V |
| ∞ | 150.04 | 0.32 | 150.01 | 0.22 | 150.01 | 0.28 | 150.02 | 0.51 |
| 138 | 150.03 | 0.30 | 150.03 | 0.26 | 150.02 | 0.25 | 150.00 | 4.06 |
| 172 | 150.00 | 0.33 | 150.01 | 0.24 | 150.03 | 0.24 | 150.05 | 4.38 |
| 229 | 149.99 | 0.37 | 150.03 | 0.28 | 150.02 | 0.23 | 150.02 | 4.66 |
| 343 | 150.03 | 0.21 | 150.01 | 0.30 | 150.02 | 0.36 | 150.02 | 4.79 |
| 686 | 150.01 | 0.18 | 149.99 | 0.25 | 150.02 | 0.21 | 150.04 | 4.98 |

| NER | Phase A | | Phase B | | Phase C | | Phase N | |
|---|---|---|---|---|---|---|---|---|
| Ω | Hz | mA | Hz | mA | Hz | mA | Hz | mA |
| ∞ | 150.04 | 43.21 | 150.01 | 43.70 | 150.01 | 44.74 | 150.02 | 49.30 |
| 138 | 150.03 | 25.82 | 150.03 | 28.03 | 150.02 | 27.67 | 150.00 | 41.39 |
| 172 | 150.00 | 22.38 | 150.01 | 24.94 | 150.03 | 24.16 | 150.05 | 32.83 |
| 229 | 149.99 | 18.44 | 150.03 | 20.76 | 150.02 | 18.59 | 150.02 | 27.83 |
| 343 | 150.03 | 12.48 | 150.01 | 14.81 | 150.02 | 13.76 | 150.02 | 26.35 |
| 686 | 150.01 | 6.40 | 149.99 | 8.96 | 150.02 | 6.95 | 150.04 | 23.18 |